A Microeconomic Perspective to Infrastructure Renewal Decisions

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Under the prevailing financial constraints and rapid infrastructure deterioration, funding decisions for renewal (rehabilitation) projects have become large challenges for engineers and economists alike. However, existing prioritization and ranking methods suffer from serious drawbacks of not considering multi-year and multi funding scenarios. Moreover, optimization efforts in the literature employ sophisticated mechanisms without providing a structured strategy or justification behind the funding solution. To overcome these drawbacks and to arrive at optimum and economically justifiable infrastructure funding decisions, this research provides a decision support system by adopting well-established concepts from the science of Microeconomics that relate to Consumer Theory and Behavioural Economics. The new decision support system has been developed with two components: (1) an enhanced benefit-cost analysis (EBCA) heuristic approach that arrives at optimum decisions by targeting equilibrium among the different renewal expenditure categories, using the equal marginal utility per dollar concept; and (2) a visual what-if analysis inspired by the indifference maps concept to study the sensitivity of decisions under different budget levels. The developed decision support system has been validated through a number of case studies including a case study were different categories of assets (pavements, bridges) are co-located. The results proved the capability of the system to arrive at optimum funding decisions supported with economic justification. Using the behavioural economic concept of “Loss-aversion”, this research also compared the strategy of minimizing loss against the typical strategy of maximizing gain in the infrastructure funding decisions. In essence, this research is aiming at improving this crucial infrastructure funding problem by integrating the two worlds of microeconomics and asset management. Such integration will help provide optimum funding decisions, increase the credibility of funding methods to the public, and justify the spending of tax payer’s money on infrastructure rehabilitation projects.

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To My Parents

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List of Acronyms

BCA	Benefit-Cost Analysis
CI	Condition Index
DI	Deterioration Index
DU	Disutility
EBCA	Enhanced Benefit-Cost Analysis
GA	Genetic Algorithm
GAMS	General Algebraic Modeling System
IE	Improvement Effect
IRI	International Roughness Index
LCA	Life Cycle Analysis
LCCA	Life Cycle Cost Analysis
MU	Marginal Utility
MU/$	Marginal Utility per dollar
RC	Replacement Cost
SF	Size Factor
U	Utility
VOC	Vehicle Operating Costs

Chapter 1

Introduction

1.1 General

The existing infrastructure in North America and all over the world has been rapidly deteriorating due to age, exposure to harsh environmental conditions, insufficient capacity to serve population growth, and insufficient funds to maintain its serviceability. In Canada, the collapse of Montreal's Ville Marie tunnel and the crumbling Champlain Bridge are indicators of Canada's infrastructure aging and deteriorating (Mcdonell, 2011). In 2008, Statistics Canada reported that Canada's infrastructure assets have exceeded about 58% of their total life span. Moreover, the continuous under-budgeting pattern and misalignment between the funds allocated and the needs has yielded a cumulative budget deficit of $123 billion (Mcdonell, 2011). In the United States, the American Society of Civil Engineers (ASCE) has published a series of report cards on the condition of 12 infrastructure categories, demonstrating almost insignificant improvement from 2001 to 2009, and the backlog in rehabilitation spending has even grown from $1.3 trillion in 2001 to $2.2 trillion in 2009 (ASCE, 2001; 2003; 2005; 2009).

The decisions to effectively distribute pre-determined funds among a large number of assets, are very challenging. Over the past three decades, many research efforts have been directed towards supporting infrastructure rehabilitation/renewal decisions. Accordingly, asset management systems (AMSs) have evolved in many domains (Uddin, et al., 2013; Halfawy, et al., 2006): pavements, bridges, water/sewer networks, and buildings. An ideal AMS includes four main functions (Vanier, 1999; FHWA, 1999): (1) inspecting the inventory of assets to evaluate their performance; (2) analyzing the deterioration behavior of various asset components; (3) quantifying the impact of various repair strategies on the performance of assets; and (4) prioritizing assets for rehabilitation purposes and allocating limited funds to various assets.

In spite of the efforts devoted to addressing the infrastructure renewal problem, it is often difficult to interpret the results, and there is a lack of mechanisms to arrive at optimal solutions in a simple explainable manner or provide sound economic justification for the fund-allocation decisions. Moreover, most of the existing decision support tools overlook the varying preferences of stakeholders and the psychological factors such as attitudes, biases, and behaviours that play an important role in the decision makers' choices.

1.2 Research Motivation

This research aims to provide an economic basis that not only can improve infrastructure fund-allocation process, but also justify the decisions made as well. The detailed research motivations are as follows:

1.2.1 Difficulty of Fund-Allocation

Decisions to effectively distribute pre-defined funds among a large number of competing assets are very challenging, particularly under the prevailing shortage in rehabilitation budgets. Moreover, with the current economic situation, tax-payers are demanding transparency and better justification behind spending the rehabilitation money (Sasmal, et al., 2007; Chou and Wang, 2012). To optimize fund-allocation decisions and achieve the highest return on the limited rehabilitation funds, a thorough benefit-cost analysis (BCA) is needed to assess the benefits (return) and the costs of a given funding decision (Higgins and Harris, 2012; Polinder et al., 2011; Adey and Hajdin, 2011), at both the individual asset level (project-level) and network-level (Uddin, et al., 2013; Barco, 1994). To integrate the two decision levels over multiple years, even for a small number of assets, the solution space becomes extremely large, and the existing BCA methods were not structured to deal with it (Vacheyroux and Corotis, 2013). Accordingly, many of the existing efforts in the literature are either focusing on project-level or network-level decisions. Some efforts tried to improve the existing fund-allocation methods by introducing life cycle cost analysis (LCCA) and optimization models that integrate both decision levels (Zhang, et al., 2013; Hegazy and ElHakeem, 2011). Optimization, however, becomes very complex and time consuming when the number of assets gets larger, and when project-and network-level decisions are integrated. As a result, most of the existing procedures endorsed by municipalities, basically leave funding decisions to the asset managers to rank assets according to subjective criteria (e.g., worst-first) and allocate funds to top ranked ones until the budget is exhausted which ends up with inefficient budget utilization (Hegazy and Elhakeem, 2011; Rogers and Grigg, 2006).

In essence, there is a lack of tools that can generate and justify optimum fund-allocation schemes in a simplified and a justifiable manner. Another challenge is the case of mixed assets, where only limited research efforts have addressed the co-location (also known as corridor rehabilitation) of infrastructure assets during rehabilitation work (e.g., above and under-ground utilities) (NRC, 2003). Therefore, there is a need to develop practical optimization models that consider the co-location of infrastructure assets in the fund-allocation decision making process.

1.2.2 Potential Use of Microeconomic Principles

Traditionally, basic microeconomic principles have been used since the middle of the 20^{th} century for understanding how consumers spend their budgets on multiple goods. Marginal utility theory (consumer theory), which is one of the well-established theories in the science of microeconomics, has been used to determine the benefits/utility gained from spending money on a certain good or service; as such, it can justify spending and the compromises made to increase the total utility (Khan, 2002). Marginal utility theory was first invented by Jules Dupuit in the mid-19^{th} century, who was known for his contributions to the benefit-cost analysis, to determine the consumers' willingness to pay for the marginal benefits gained from projects (Arler, 2006).

This research, thus, enhances the existing BCA methods by reviving its origins and using the consumer theory concept of marginal utility to improve the existing fund-allocation methods and determine optimum decisions in a simple yet justifiable way. The basic premise of this research is the analogy between the infrastructure situation where there is a limited budget from the tax payers' money that needs to be optimally spent on different infrastructural renewal programs, and the consumer situation who has a limited budget that needs to be invested optimally on the different desired spending categories to maximize his/her utility (i.e., benefit) (Lipsey et al., 1997; Fozzard, 2001; Rahman and Vanier, 2004; Parkin & Bade, 2009). This research adopts two concepts that have potential application in the infrastructure domain: Equal marginal utility per dollar, and Indifference curves. The equal marginal utility per dollar concept can arrive at the consumer's optimal choice in a structured way by equating the marginal utility per dollar spent on all expenditure categories rather than the typical approach of maximizing total utility, while fully consuming the budget available. As such, it represents a simple practical heuristic approach that can optimize, balance, and justify decisions. The indifference curves concept provides a visual approach to determine the impact of different budget limits on the optimum choices, and on the preferences of decision makers (Lipsey, et al., 1997; Parkin and Bade, 2009). In essence, the two microeconomic concepts have the ability to help decision makers explain the optimal result and properly allocate funds considering utility gained from money spent; therefore, they have the potential to be adopted, and tested in the infrastructure domain (These two concepts will be further discussed in Chapter 2).

1.2.3 Potential Use of Behavioural Economics

Behavioural economics, in general, takes into account psychological feelings that reflect the preferences of consumers/decision makers. Thus, it has great potential in mission-critical domains such as infrastructure asset management as it involves many stakeholders (municipalities, funding bodies, tax payers, consulting companies, and users) with diverse priorities and perceptions, which need to be captured in the decision making process. However, it involves many risky decisions with large economic implications, including: asset prioritization, fund allocation, privatization, resource planning, management philosophy, etc. Many of these decisions involve elements of experience, intuition, and subjective judgment. To support these difficult decisions, researchers strive to develop adequate decision support systems to guide human experts and avoid possible human misjudgements. The extensive body of knowledge since the 1990s on artificial intelligence (AI) applications in construction engineering and management and other domains, for example, represent efforts to support difficult decisions (Negnevitsky, 2005). AI and other decision support tools, however, share the quest to rationalize problem solving and maximize benefits (utility or gain). This assumption of rationality has lately been a major subject of debate, particularly in the emerging field of behavioural economics, which examines the impact of psychological factors such as human attitudes, biases, and behaviours on economic decisions (Kahneman, 2003). Many subjective decisions in the infrastructure domains are influenced by attitudes, biases, and behaviours of stakeholders; as a result, the best decisions may not often seem the most rational, hence the psychological factors playing an important role in these decisions need to be considered.

This research, thus, introduces common behavioural economic concepts and examines the influence of the most influential behaviour “Loss-aversion” on infrastructure fund-allocation decisions, as opposed to the traditional approach of maximizing utility (i.e., from the gain point of view). The use of the “loss-aversion” concept can help provide a different fund-allocation strategy by framing the problem to minimize losses resulting from delaying repairs or not repairing some assets. As such, studying the field of behavioural economics would be of great value as it complements the research on practical decision making, and can potentially improve infrastructure renewal decisions and adjust the current methodologies to account for different perspectives.

1.3 Research Objectives and Scope

The goal of this research is to improve the economics of infrastructure renewal decisions. It will address the two challenging aspects of infrastructure rehabilitation:1) the multi-level complexity of the infrastructure fund-allocation problem; and 2) the influence of behaviours and the different stakeholders' preferences on the decision-making process, in a simplified and a justifiable manner inspired by the broad array of concepts in the science of microeconomics. The detailed objectives of this research are:

- Understand the prevailing techniques for infrastructure funding, and study the microeconomic principles that relate to optimal choices, as well as the different aspects of behavioural economics that can be utilized in the infrastructure domain;
- Develop a microeconomic testing tool that can be used to examine the quality of any fund-allocation mechanism;
- Develop a microeconomic-enhanced benefit-cost analysis (EBCA) heuristic approach for improving fund-allocation decisions at the network-level, using the law of equal marginal utility per dollar. This new approach can achieve equitable and optimum distribution of funds, while being able to justify the decisions;
- Develop a new visual what-if analysis tool, inspired by the indifference maps concept, that provides a visual representation of all possible decisions to facilitate studying sensitivity of decisions under any imposed changes;

- Incorporate different behavioural perspectives into infrastructure rehabilitation decisions to capture their influence on the decision making process; and
- Integrate the co-location of assets into the infrastructure decision-making process.

In essence, this research aims at providing a decision support system for fund-allocation coupled with a solid economic basis that can justify the allocation of tax-payers' money on different infrastructure programs.

The four main thesis hypotheses can be formulated as follows:

1. Consumer theory of microeconomics applies to infrastructure domain, and the optimum fund-allocation decision, according to this theory, is an equilibrium state at which the marginal utility per dollar (MU/$) spent on all funding categories is balanced;
2. Framing the objective of fund-allocation optimization in terms of Loss-aversion can result in a different funding strategy, and a new decision perspective, as compared to using an objective in terms of gain-seeking;
3. EBCA heuristic approach can achieve equitable and optimum distribution of funds, while being able to justify the decisions in a simple, structured way; and
4. Large-scale projects, including mixed assets case, are easier to handle using the EBCA approach due to the huge reduction of the solution space.

1.4 Research Methodology

The methodology for achieving the mentioned objectives is as follows:

1. Conduct a comprehensive literature review of:
    a. The different LCCA and BCA models for infrastructure fund-allocation;
    b. The different models that address renewal of co-located assets;

c. The microeconomic principles, marginal utility per dollar and indifference curves, that are addressed to maximize the return on money while allocating funds under constrained budgets; and

d. The concept of behavioural economics and its impact on the decision making process.

2. Develop general LCCA and mathematical optimization models;
3. Apply the optimization model on two real case studies of 800 building components and 1300 pavement sections, and examine the network-level decisions with respect to the microeconomic concepts to validate the concept of adopting microeconomic principles into the infrastructure domain, and of having a stand-alone microeconomic testing tool;
4. Modify the objective function of the mathematical optimization model to incorporate the loss-aversion perspective with respect to different stakeholders preferences, and compare against the typical approach of maximizing gain (i.e., utility maximization);
5. Develop a generic microeconomic-enhanced benefit-cost analysis (EBCA) heuristic approach;
6. Apply the new EBCA model to a real case study of 800 buildings components to represent its features and develop a simplified optimization model to facilitate finding the optimum solution;
7. Validate the newly developed EBCA approach by comparing the results against the results obtained using the existing optimization models with respect to different criteria (e.g., quality of solution, solution space, number of variables, level of complexity, explainable, etc.);
8. Extend the concept of indifference curves by developing a colour coded contour map that shows both the total utility and the total cost that associate any selection of assets. Apply the new visual what-if analysis tool to the building case study data to show its features and its potential to be extended to visualize multiple asset categories; and
9. Apply the EBCA approach to a mixed assets case study to demonstrate its features, and affirm its applicability in handling large-scale problems.

1.5 Research Organization

The main core of the thesis is depicted in Figure 1.1; however, the thesis is organized as follows:

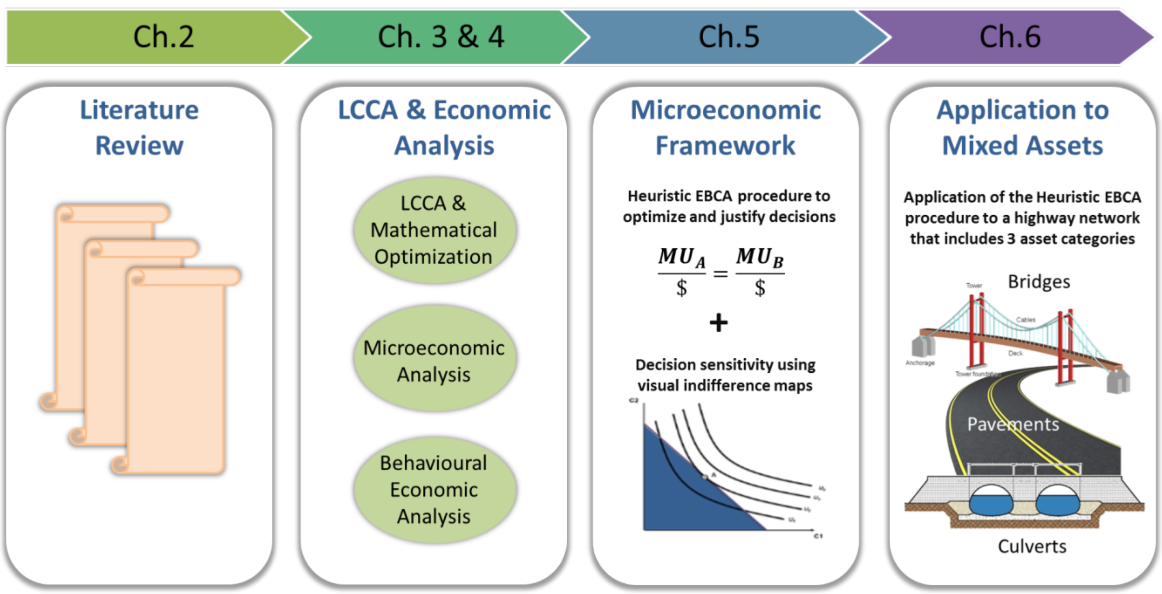


Figure 1.1 Thesis Structure

Chapter 1: This chapter introduces the challenges associated with infrastructure rehabilitation/renewal, the potential of integrating the two worlds of microeconomics and asset management, research motivation, research objectives and hypotheses, and research methodology.

Chapter 2: This chapter provides a comprehensive review of benefit-cost analysis. It reviews its origins and discusses the existing efforts in the infrastructure domain. It discusses as well the concept of coordinating co-located infrastructure work and how it may potentially affect the fund-allocation process. It also provides a brief insight into the microeconomic and behavioural economics concepts that this research adopts as a methodology for improving infrastructure renewal funding, along with the existing efforts that tackled these concepts.

Chapter 3: This chapter describes two real case studies of two different asset networks that are used to examine the proposed methods in this research. The chapter describes, as well, a general mathematical optimization model and its implementation on both case studies for the purpose of investigating the level of complexity associated with them, and to be used as a benchmark to affirm the quality of the solutions provided by the proposed EBCA approach in this research.

Chapter 4: This chapter examines several economic concepts in the infrastructure domain, in order to provide better justification for infrastructure fund-allocation decisions. It tests the applicability of equal marginal utility per dollar in the fund-allocation problem, by analyzing the optimum decisions obtained for the case studies in Chapter 3, with respect to this theory. This chapter also investigates the influence of behaviours on funding decisions by framing the mathematical optimization models of Chapter 3 to consider the loss-aversion perspective, and comparing the results to the traditional gain-seeking approaches.

Chapter 5: This chapter describes the new microeconomic-based decision support framework that incorporates two main components: (1) An enhanced benefit-cost analysis (EBCA) heuristic approach; and (2) A visual sensitivity analysis tool. It explains step-by-step the development of the proposed heuristic approach, and its implementation on real case studies both manually and using a simple optimization model.

Chapter 6: This chapter describes the application of EBCA heuristic approach on a mixed assets case study where multiple assets are co-located and competing for funding. Also it describes the earlier efforts that addressed this case study, and the approaches used.

Chapter 7: This chapter discusses the research conclusions, contributions, and the future research work.

Chapter 2

Literature Review

2.1 Introduction

This chapter provides an insight into the infrastructure fund-allocation problem along with a comprehensive review of benefit-cost analysis. It reviews the origins of benefit-cost analysis and discusses the existing efforts in the infrastructure domain. It discusses as well the concept of coordinating co-located infrastructure work and how it may potentially affect the fund-allocation process. It also provides a brief insight into the consumer theory which is one of the basic microeconomic principles that this research adopts as a methodology for infrastructure renewal funding, along with the existing efforts that tackled this concept. Finally, it discusses the different aspects of behavioural economics, including the most common behaviour “loss-aversion”, and their potential for improving infrastructure funding decisions.

2.2 Infrastructure Fund-allocation

In general, allocating funds follows a long budgeting process that starts with internal approval, external adoption, etc., and ends up with the actual allocation of funds required in the operation of an organization (Wooldridge et al., 2001). Budgeting process, however, is more than just allocating the limited budgets to different sectors; it is more about compromises among the requirements of the various sectors/assets. Barco (1994) discussed two common budgeting models for infrastructure maintenance and repair: 1) the Based-budgeting model; and 2) the Zero-based-budgeting model. The first model uses the incremental approach method that increases the previous allocated budgets by small increments and avoids radical and risky leaps in policy from one year to another; while the second method uses the performance-based approach that re-evaluates projects through continuous monitoring of the performance, and reallocates funds as efficiently as possible. Wooldridge et al. (2001) also discussed the various types of budgeting models (e.g., incremental vs. performance-based), and highlighted their effects on the practices of the infrastructure capital allocation process.

Allocation of limited predefined renewal funds internally to many assets is even more challenging than the allocation of budgets to sectors/capital projects, due to the difficulty of satisfying the needs of all projects (Teng, et al., 2010). Moreover, selling Maintenance and Repair (M&R) (i.e., convincing the budgeting agencies/public to fund assets for repair) is a challenging task too, due to the common attitude “if it ain't broke, don't fix it”, and also due to the hidden nature of most M&R problems (Barco, 1994). In the infrastructure fund-allocation problem, decision makers are faced with the problem of deciding which assets need to be considered for funding, what renewal strategy to use, and when to do renewals, etc. (Uddin, et al., 2013). Answering these questions needs a comprehensive infrastructure life cycle analysis (LCA) that involves several main stages, starting from inspection to fund-allocation, as shown in Figure 2.1.

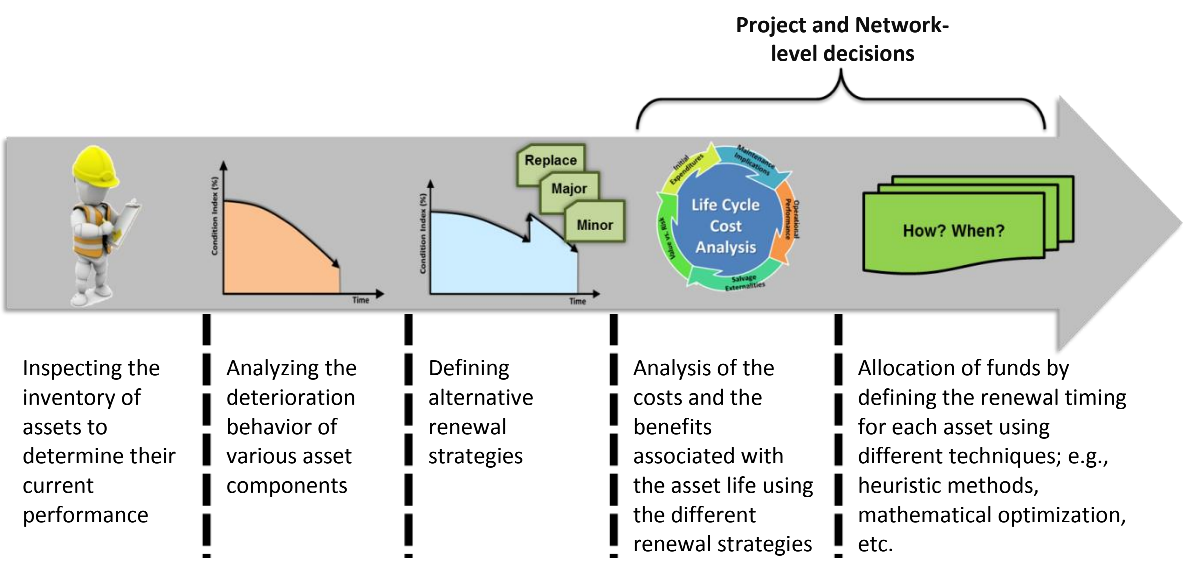


Figure 2.1 Main stages of infrastructure asset renewal (based on Hegazy and Elhakeem, 2011)

The last two stages involve project-and network-level analyses that are mainly concerned with what renewal strategy to use, and when to do renewals, respectively (Haas, 2001). To optimize decisions considering both project-and network-levels, a thorough benefit-cost analysis (BCA) is needed at both levels. Decision makers need to assess the benefit (return) of a given decision with respect to its cost to achieve the highest return on the limited rehabilitation budget (Higgins and Harris, 2012; Polinder, et al., 2011). Since this research focuses on fund-allocation economics, it only focuses on the last two stages as highlighted in Figure 2.1, while the other LCA stages are not discussed in this literature review.

2.3 Benefit-Cost Analysis (BCA)

Benefit-cost analysis (BCA) basically evaluates the benefits and costs associated with one or several investment options to select the best alternative (Thoft-Christensen, 2012; Fraser and Jewkes, 2013). An investment is considered acceptable if its expected benefits exceed its expected costs. For a set of independent alternatives under unlimited funds, all investments with benefits exceeding costs are considered acceptable. When a set of mutually exclusive alternatives exists; acceptable alternatives are first filtered and ranked according to the initial cost (least cost investment is more preferred), then an incremental comparison is carried out among them, starting from the top ranked. An alternative becomes more preferred than the current preferred one, if its incremental benefits are higher than its incremental costs, and so forth until the best investment option is determined (Fraser and Jewkes, 2013). BCA originally evolved from a series of articles written by two French engineers, Auguste Cournot and Jules Dupuit in the mid-19th century, who were known as the founding fathers of microeconomics (Arler, 2006). Jules Dupuit, in particular, was known for his contribution to the benefit-cost analysis. He developed the concept of consumer surplus (or relative utility) while analyzing the optimal capacity of a canal project (Lund, et al., 2006; Ekelund, 1968). He invented the “marginal utility” theory that is concerned with the consumers’ willingness to pay for the marginal benefits gained from projects (Arler, 2006). For instance, he analyzed the effect of imposing tolls on the marginal number of passages over a bridge. He was entitled the intellectual "father" of benefit-cost analysis in the 19th century, especially after his outstanding article “On the Measure of the Utility of Public Works” (NCEE, 2013).

Formal BCA, however, wasn’t applied until 1936 when the US Flood Control Act asked for a thorough feasibility test for flood control projects to make sure that the benefits exceed the costs (NCEE, 2013; Arler, 2006). Afterwards, BCA has become an essential tool in governmental decisions and a part of the US public administration. Later in 1950, the “Green Book” report set the standards for using benefit-cost analysis in public investments. In 1981, BCA was officially recognized as a basic tool in US federal planning (Arler, 2006) to assess the losses and gains, guarantee highest return over the money spent, and gain the public support. For instance, the United States National Institute of Standards and Technology (NIST) developed benefit-cost models for ranking projects with acceptable benefit-cost ratios, when there is insufficient funding for all of them (Fuller and Petersen, 1996). In Canada as well, the Canadian Cost-Benefit Analysis Guide (Treasury Board of Canada Secretariat, 2007) is one of the main guidelines to assist analysts with the decision making in the public sector, especially when projects involve social, economic, and/or environmental impacts (Fraser and Jewkes, 2013).

Table 2.1 summarizes the common existing approaches to evaluate alternative decisions, with samples of the research efforts that use each method. Net Present Value (NPV) and BCR (methods 1 and 2 in Table 2.1), are the most common in the public sector (Fraser and Jewkes, 2013; Treasury Board of Canada Secretariat, 2007; European Commission, 2008), and to gain public support for projects (Choi, et al., 2009). BCR approach is even more common when there are budget constraints. Both methods use monetary values for both benefits and costs. However, many complex problems, including infrastructure renewal, involve multiple benefits (e.g., economic, environmental, social, etc.) which cannot be easily converted to dollar values (Fraser and Jewkes, 2013). In the literature, several efforts have introduced approaches, such as Cost effectiveness, and cost utility approaches (methods 3 and 4, respectively in Table 2.1), to model the benefits that involve non-monetary units (natural units or utility scores) (Higgins and Harris, 2012; Polinder et al., 2011; Moayyedi and Mason, 2004). Such approaches are more suitable for infrastructure rehabilitation problems. The last three methods in Table 2.1, on the other hand, select the choices that either maximize benefits or minimize costs, independently (Hajkowicz, et al., 2008).

Table 2.1 Approaches for analyzing costs and benefits of alternative decisions

	Comments	**Sample of related research**
Net Present Value (NPV)	Uses monetary values for both benefits and costs. The alternative with the highest positive value is the preferred one.	Rehabilitation of transportation networks (Orabi and El-Rayes, 2012). Evaluation of infrastructure projects (European Commission, 2008) Infrastructure renewal timing decisions (Pudney, et al., 2006)
Benefit-Cost Ratio (BCR, B/C or B/$)	Uses monetary values for both benefits and costs. For mutually exclusive alternatives, incremental benefit-to-cost ratio is used.	Bridge maintenance (Adey and Hajdin, 2011) Ranking of bridge investments (Vacheyroux and Corotis, 2013).
Cost Effectiveness (CE, or E/$)	Benefits can be monetary or non-monetary. However, it is difficult to combine different types of benefits and compare alternatives across different domains.	Pavement treatment selection (Khurshid, et al., 2013; Irfan, et al., 2009) Pavements treatment using CE index(Singh, et al., 2007; Labi and Sinha, 2005) Pavement investments (Haas, et al., 2006)
Cost Utility (CU, or U/$)	Special case of cost-effectiveness. Benefits are represented in the form of utility scores that can integrate different types of benefits and can better represent the preferences of individuals or society.	Water planning (Marinoni, et al., 2011) Water investments (Hajkowicz ,et al., 2008)
Utility Maximization Max(U)	Maximizes utility within a pre-defined budget	Materials selection (Karande, et al., 2013) Transportation infrastructure fund-allocation (Gharaibeh, et al., 2006)
Benefit Maximization Max(B)	Maximizes benefits or effectiveness within a pre-defined budget.	Resource allocation in rehabilitation projects (Shohet and Perelstein, 2004) Pavement asset management (Chou and Wang, 2012)
Cost minimization Min ($)	Minimizes the total cost among a set of choices. Can be beneficial in case of equal benefits among alternatives.	Concrete-Anchors selection for connections (Olsen, et al., 2007) Infrastructure rehabilitation (Yeo et al., 2013; Chou and Wang, 2012)

2.3.1 BCA Efforts for Infrastructure Renewal

In the infrastructure domain, public agencies are facing a huge challenge to sustain the safety and operability of their deteriorating infrastructure, particularly under the prevailing shortage in rehabilitation budgets. In addition, tax-payers are demanding transparency and better justification behind spending the rehabilitation money (Sasmal, et al., 2007; Chou and Wang, 2012; Adey and Hajdin, 2011).

Infrastructure renewal is a multi-asset multi-year problem where a limited pre-defined yearly budget needs to be efficiently allocated among the needy assets so that to attain the highest return over the budget. Such problem usually involve hundreds of assets, in addition to multiple benefits (monetary and/or non-monetary), multi-year plans, and multi-repair options for each asset. The existing NPV and BCR methods are not structured to deal with the complexity of modeling this problem considering all the deterioration behaviours of each asset, all the alternative repairs, and years.

To support funding decisions for infrastructure renewal, a comprehensive benefit-cost analysis is needed at both project- and network-level decisions over multiple years to assess the benefits and costs associated with each decision and achieve the highest return on the limited budgets available. Such analysis can help determine the best combination of renewal strategy (m), and renewal year (j) for each asset (i) respectively, as shown in Figure 2.2. Thus, even for a small scale problem, the solution space becomes extremely large, and the existing BCA methods were not structured to deal with it (Vacheyroux and Corotis, 2013). Accordingly, most of the existing models in the literature are either focusing on project-level or network-level decisions. At the project-level, benefit-cost ratio (BCR) or cost-effectiveness (CE) has been often used to evaluate the benefits and costs of the different available renewal/repair strategies for a given asset (e.g., Khurshid, et al., 2013, Adey and

Hajdin, 2011). At the network-level, some research efforts in the literature have introduced optimization models in different asset domains, including: pavements (De la Garza, et al., 2011); water networks (Dridi, et al., 2008; Mann and Frey, 2011).

Some efforts tried to improve the existing fund-allocation methods by introducing optimization models that integrate both decision levels while considering the various benefits and costs associated with rehabilitation options, yet with different objectives and constraints (e.g., minimize cost under performance constraint; or maximize performance under budget constraint, etc.). Zhang et al. (2013), for example, used backward dynamic programming to formulate life cycle analysis (LCA) to determine optimum preservation strategy at the project-level for a pavement management system. Then this model was integrated with a network-level model using binary integer programming to minimize life cycle energy consumption, greenhouse gas emissions, or costs as a single objective. Hegazi and Rashedi (2011) as well used benefit-cost ratio (BCR) analysis, and Genetic algorithms optimization for project and network levels of decisions, respectively, and later developed a mathematical optimization model at the network-level (Rashedi and Hegazy, 2014) to handle large-scale asset networks with an objective of maximizing the overall network performance. Patidar et al. (2007) also have documented in the NCHRP 590 report, an integrated approach that selects bridges at the network-level from a sorted list in a descending order according to incremental utility-cost ratio of the candidate bridge intervention at the project-level. The candidate interventions are evaluated using an incremental comparison across the different available interventions for each bridge with an overall objective of either meeting performance or budget constraints at the network-level. However, in case of budget constraint which is the case for most agencies (Haas, 1978), such approach can lead to not fully exhausting the budget available (Patidar, et al., 2007). Elbehairy et al. (2006) and Miyamoto, et al. (2000) used Genetic Algorithm to integrate both levels for bridge management system. Tong et al. (2001) used genetic algorithm as well to optimize buildings renewal expenditures.

While these efforts provided useful LCCA models, most of them formulated the problem in the form of a combinatorial optimization problem while targeting maximizing benefits, thus lacking a satisfactory justification behind the optimization results. The results are typically a set of decisions (usually binary, i.e., a combination of [0, 0, 1, 0, 0] represents a decision to repair an asset in year 3 of a 5-year plan). In case thousands of assets are involved, which is typical, the combination of zeroes and ones is not easy to examine, interpret, or justify. Several combinations of zeroes and ones can lead to close-to-optimum solutions, and thus it is not easy to determine the "strategy" behind those solutions.

Accordingly, in current practices, BCR approach has been mainly used at the project-level to select the renewal strategy with the highest benefit-cost ratio (BCR). Network-level funding decisions, on the other hand, are left to the asset managers on the basis of worst-first or considering multiple criteria (condition, age, material, maintenance history, customer complaints, etc.) to rank the assets and allocate the budget to top ranked ones until the budget is exhausted (right side of Figure 2.2), which ends up with inefficient budget utilization (Hegazy and Elhakeem, 2011; Rogers and Grigg, 2006).

In essence, there is a lack of tools that can generate and justify optimum fund-allocation schemes. This research, therefore, attempts to capitalize on the well-established consumer theory of microeconomics and proposes a microeconomic-inspired enhancement to the benefit-cost analysis, to handle the multi-level complexity of the infrastructure fund-allocation problem in a simplified and a justifiable manner.

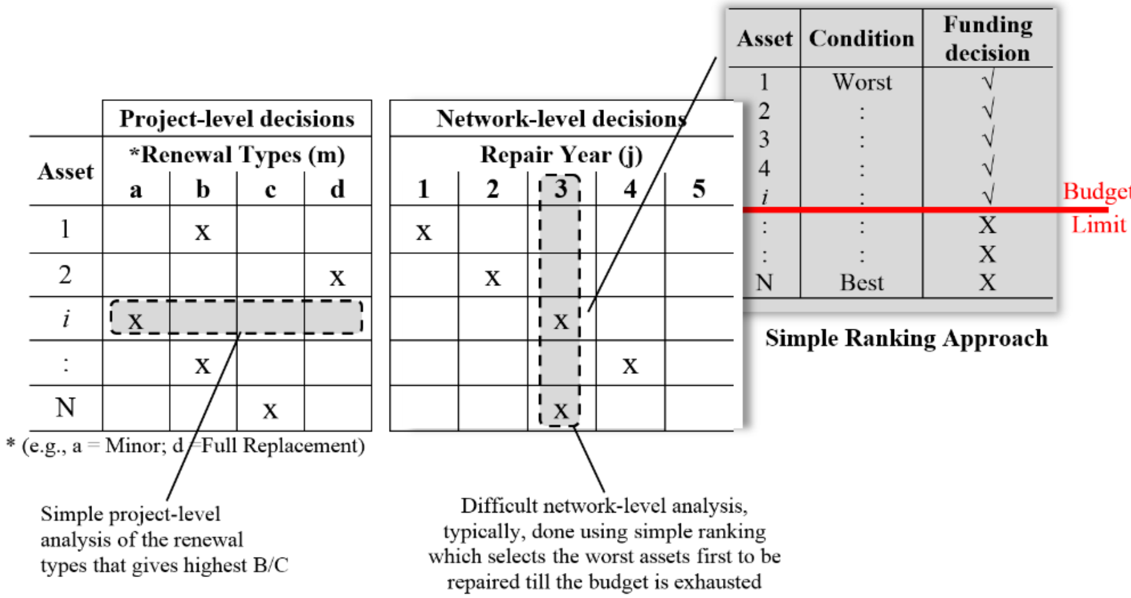


Figure.2.2 Bi-level scope of the infrastructure renewal problem

2.4 Coordination of Interrelated Infrastructure Works

Infrastructure assets have a unique, distinct, and complex nature, due to their interrelationships and interdependencies (e.g., above and under-ground utilities). This sophisticated nature of infrastructure assets requires different areas of knowledge and expertise within each municipal department (pavement, water, sewer, etc. management). Most of the existing management systems, however, deal with these departments as isolated units resulting in much inefficiency, especially in coordinating rehabilitation work, due to complexity of exchanging massive information and difficulty of streamlining between these departments (Halfawy, 2008). In order to implement efficient and optimized infrastructure management strategies, adopting integrated approaches among the different infrastructure departments has become a necessity. Such approaches will help integrate infrastructure data, coordinate the decision making processes, and accurately manage the asset life cycle data, thus eliminating the fragmentation inefficiencies (Halfawy, 2008).

Some research efforts have referred to the rehabilitation of interrelated infrastructure assets as coordination of infrastructure rehabilitation works or corridor rehabilitation of co-located assets (NRC, 2003; Shahata and Zayed, 2010). The rehabilitation of an entire corridor, when all the assets have deteriorated enough, can help reduce unnecessary rework, disruption, social costs, and risks associated with maintenance operations (NRC, 2003; Halfawy, 2008). For example, municipalities can consider the rehabilitation of a road and the underlying utilities such as water, sewer, and drainage systems simultaneously at a certain point in their life spans (Osman, et al., 2013). Other municipalities can start in an opposite direction by considering the water system, then upgrading all the adjacent underground systems, and finally repaving the road above (NRC, 2003). However, there are some concerns regarding the economic life lost due to premature replacement of some infrastructure components as part of the whole corridor replacement, such that the economic benefits of corridor replacements are not sufficient to justify the lost economic life of the asset. Therefore, an economic analysis should be carried out to investigate the trade-off between economic life lost due to premature replacement and the cost avoided by repeated pavement repairs and social disruption to the area (NRC, 2003).

In the literature, some research efforts have tackled the integration/coordination of the infrastructure data among the different departments. El-Diraby (2002), for example, proposed a theoretical framework for a web-based system for coordinating infrastructure environments. Later, El-Diraby (2006) presented a roadmap for a web-based environment for coordinating infrastructure project development. Halfawy (2008) developed an integrated municipal infrastructure management environment (MIMEs) that includes water, sewer, road, etc., networks that are distributed among different departments. The model considered the coordination of infrastructure work processes through centralized shared data repositories and an extensible wide software environment for the integration of the distributed stand-alone software tools. This work proposed both VL integration within each department and HL integration among the different departments.

In one interesting study, Shahata and Zayed (2010) developed a methodology to optimize the corridor rehabilitation decisions of co-located road, water, and wastewater networks. The methodology consists of 1) risk analysis; 2) performance evaluation; 3) condition assessment; 4) data collecting and analysis; 5) documentation of the obstacles/barriers to the corridor rehabilitation, 6) decision tree analysis to plan for intervention, inspection, and revisiting during subsequent planning cycles; and 7) genetic algorithm optimization to determine the optimum repair/renewal cost and replacement interval. The model utilized GIS to identify the co-located assets and their different characteristics at each segment to determine the driving assets (most deteriorated) for rehabilitation. For example, if the sewer is the driving asset of a certain corridor, then the following alternatives will be considered: 1) replace the sewer from manhole to manhole and the co-located water and road segments of an equivalent length; 2) if the sewer segment is smaller than the water segment, then replace the sewer and the road segments to a length equivalent to the water segment; or 3) replace the sewer segment from manhole to manhole, the water segment from node to node, and the road segment that is equivalent to the longer sewer and water segments.

In essence, coordinating infrastructure renewal works has a great potential for application as it can help increase the reliability of infrastructure providers and reduce the disruption and the social costs associated with rehabilitation work.

2.5 Applicable Microeconomic Principles

According to the origins of BCA that Jules dupuit has initiated (Lund, et al. 2006; Ekelund, 1968), one of the basic Microeconomic principles that has potential application for fund-allocation is the

“Theory of Consumer Behaviour”. A consumer is one of the major decision makers in an economy, who usually seeks to maximize his/her utility (a common economic measure of satisfaction) in his consumption decisions (Chugh, 2008). Thus, consumer theory has been studied since the middle of the 20^{th} century for understanding how consumers optimally spend their limited budgets on multiple goods (Khan and Hildreth, 2002). In this theory, consumers look for affordable combinations of goods that maximize their total utility over the money spent (benefit or satisfaction) (Lipsey, et al., 1997; Fozzard, 2001; Rahman and Vanier, 2004; Parkin and Bade, 2009). The consumer situation is analogous to the situation of a government agency trying to allocate a limited budget from the tax payers’ money to multiple programs to maximize the return (utility) over the allocated tax payers’ money. Two basic theoretical concepts of consumer theory have potential benefits in asset management: Law of Equi-marginal utility per dollar to be used as a decision support system to arrive at optimum balanced fund-allocation decisions and to examine the quality of any funding mechanism, and Indifference Curves to facilitate studying visually the sensitivity of decisions under any imposed changes (e.g., budget levels). These concepts are discussed in the following subsections.

2.5.1 Law of Equi-Marginal Utility per dollar

Consumer theory provides approaches for determining the optimum combination of goods that maximizes the consumer’s utility. There are two concepts of utility: Total Utility and Marginal Utility (Parkin and Bade, 2009). *Total Utility* is the total benefit or satisfaction a person gets from the consumption of goods (more consumption gives more utility). The *Marginal Utility* is the change in total utility that results from a one unit increase in the quantity consumed of a good. As the quantity consumed of a good increases, the marginal utility from consuming it decreases (i.e., the consumer gets less satisfaction with each extra subsequent unit he/she gets). This phenomenon of decreasing marginal utility is called *diminishing marginal utility* (Parkin, 2009).

To demonstrate the basic concepts of consumer theory, a simple example, based on Parkin and Bade (2009) text book examples, is used. The example is of a consumer who would like to maximize his/her benefit from spending a limited income of $40 on two products (e.g., candy bars and fruits): X ($4/unit); and Y ($8/unit). The basic information about the consumer's utility (satisfaction) from both products is shown in Table 2.2. It shows the total utility (TU) and the marginal utility (MU) that correspond to each unit consumed from each product. As consumption increases, the marginal utility decreases (e.g., the consumer's satisfaction from the 2nd unit of product Y is 40, which is less than his/her satisfaction from the 1st unit which is 50).

One approach to determine the optimum combination of both products, that achieves the maximum total utility and fully consumes the available budget, is trying different random combinations. Figure 2.3, for example, shows the analysis of six combinations of X and Y products (each combination in a row) that consume the $40 budget (e.g., 8 X units and 1 Y unit; or 4 X units and 3 Y units, etc.) along with the sum of the total utility associated with each combination in the last column of the table. Thus, the optimum combination is the one that achieves maximum consumer total utility, which is (6 X units and 2 Y units), giving the highest total utility of 315 [(75+48+36+24+22+20) for the first six X units + (50+40) for the first two Y units]. While Figure 2.3 presented this example in an easy-to-solve manner, typically such problem needs to be formulated as an integer optimization problem to determine the amount to be purchased from each product by maximizing the sum of total utility under the budget limit. As a result, it would be time-consuming and involve high degree of complexity for larger scale problems. As an alternative approach to solve the above example, consumer theory provides an interesting heuristic approach to arrive at the same optimum decision. In this approach, the consumer chooses the combination of products that achieves an equilibrium state at which the marginal utility gained per dollar spent on the last unit consumed from each product is equal, and fully consumes the budget available (Lipsey, et al., 1997). As such, a combination of x units of X product plus y units of Y product is optimum when:

$$\left(\frac{MU}{\$}\right)_{xth} = \left(\frac{MU}{\$}\right)_{yth} \tag{2.1}$$

Table 2.2 Consumer's satisfaction from each additional unit per product

Unit Number	Product X ($4/unit)		Product Y ($8/unit)	
	Marginal Utility (MU)	Total Utility (TU)	Marginal Utility (MU)	Total Utility (TU)
1st	75	75	50	50
2nd	48	123	40	90
3rd	36	159	32	122
4th	24	183	28	150
5th	22	205	26	176
6th	20	225	24	200
7th	13	238	22	222
8th	10	248	20	242
9th	7	255	17	259
10th	5	260	16	275

Product X ($4/unit)		Product Y ($8/unit)		Total Utility from both
Quantity	Total Utility	Quantity	Total Utility	
10	260	0	0	260
8	248	1	50	298
6	225	**2**	90	**315**
4	183	3	122	305
2	123	4	150	273
0	0	5	176	176

Optimum combination (2+6) has highest total utility.

Six possible combinations of Products X and Y that fully consume the $40 budget

Figure 2.3 Optimization of consumer choices using total utility maximization

The mathematical proof of Equation 2.1 is provided in Appendix I. Using this approach, the optimum combination is determined to be a combination of 6 units of X product and 2 units of Y product since the MU/$ gained from the 6th X unit = MU/$ gained from the 2nd Y unit = a value of 5, as shown in Figure 2.4.

This result is the same as the one obtained by total utility maximization. The logical process to arrive at this optimum combination starts by the consumer evaluating the return (MU/$) from each product, and then successively selects the ones with the highest MU/$, one-by-one, until the budget is exhausted. At the end of this process, the available money is fully spent and the consumer accumulated the choices with the highest return (6 X units and 2 Y units), that achieve a balanced satisfaction from both products. Since the optimum combination using the law of equi-marginal utility per dollar (MU/$) is identical to the one obtained from total utility maximization; therefore, this law can reach optimum solution through balanced and fair allocation of money to different categories of spending, without complex optimization. Thus, it has the potential application in the infrastructure fund-allocation problem to help determine optimum decisions supported with sound economic justification.

Product X ($4/unit)			**Product Y ($8/unit)**		
Quantity	Marginal Utility (MU)	MU per dollar	Quantity	Marginal Utility (MU)	MU per dollar
10	5	1.25	0	0	0
8	10	2.50	1	50	6.25
6	20	5.00	**2**	40	5.00
4	24	6.00	3	32	4.00
2	48	12.00	4	28	3.50
0	0	0	5	26	3.25

Optimum combination (2+6) has equal MU/$ in all categories

$(MU/\$)_X = (MU/\$)_Y$

Equating MU per dollar for all categories achieves same optimum results reached in Figure 2.3

*Marginal Utility= level of satisfaction in consuming the n^{th} unit.

Figure 2.4 Optimization of consumer choices using Law of Equi-Marginal utility per dollar

2.5.2 Indifference Curves

This important microeconomic concept visually maps the whole space of possible consumer decisions and their associated total utilities. Each indifference curve is a curved line that represents several combinations of goods which the consumer is indifferent about (i.e., giving the same level of total utility) (Parkin and Bade, 2009; Chugh, 2008). For example in Table 2.2 for the previous consumer case, a combination of 3 X units and 4 Y units gives total utility of 309 which is almost equal to the total utility of a combination of 6 X units and 2 Y units (315). The consumer is almost indifferent about both, thus they lie on the same utility curve as shown in Figure 2.5a. By connecting all the combinations that gives similar total utility, the indifference map of curves can be formed, where each curve represents a different level of total utility. The indifference map shows all the possible combinations, including those below and above the budget limit. Since the consumer is limited by his/her available budget, it is possible to graphically represent the choices that fully exhaust the available budget by plotting the following equation for two goods X and Y (Lipsey, et al., 1997; Parkin and Bade, 2009; Chugh, 2008):

$$x.P_x + y.P_y = B \tag{2.2}$$

Where, *x* is the quantity purchased from product X; P_x is the unit price of product X; y is the quantity purchased from product Y; P_y is the unit price of product Y; and B is the available budget. Equation 2.2 represents the budget line, as shown in Figure 2.5b (Lipsey, et al., 1997). This line represents all the combinations of both products that fully exhaust the budget, which are the same six combinations in Figure 2.4. Having both the indifference map and the budget line, it is possible to merge them to graphically determine the optimum combination of X and Y products that yields the highest utility (i.e., lies on the highest indifference curve), and also satisfies the budget constraint (i.e., lies on the budget line), as shown in Figure 2.5b (Chugh, 2008).

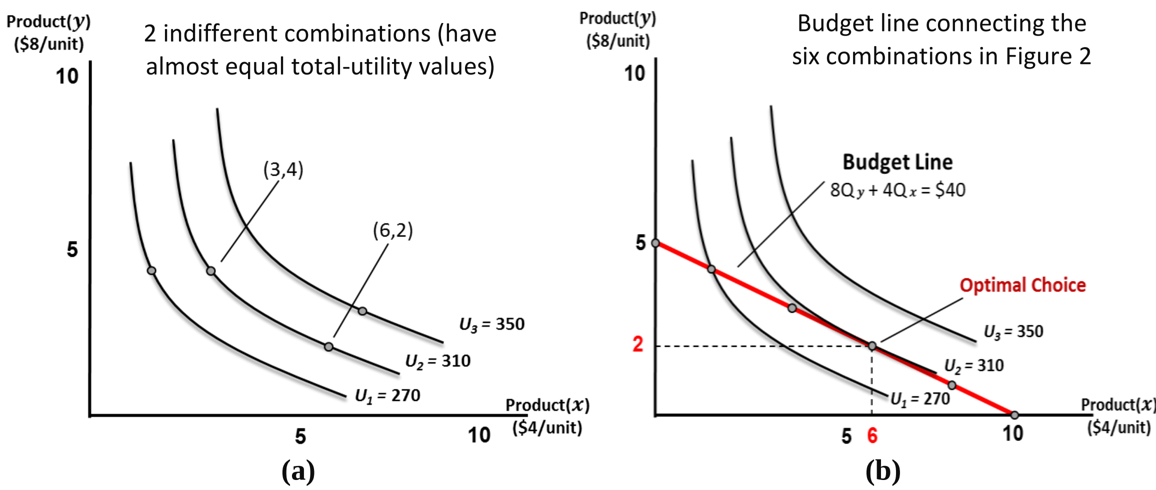


Figure 2.5 Indifference curves concept

The importance of the indifference curves is their ability to visually articulate the benefits (utilities) of all possible decisions, and also to determine the optimum decision graphically. Moreover, it can be used to test the impact of variation in budget levels on the optimum decision. In the infrastructure domain, no comparable analysis exists to visualize funding decisions and their sensitivity.

2.5.3 Existing Economic-based Research

Few researchers approached the earlier described microeconomic concepts to find a solution for government spending. Nagel (1985), for example, developed a study that attempted to optimally allocate federal money to ten cities to reduce their crime rates. The study used the marginal rate of return MRR approach and found that the optimum allocation was to allocate money such that all of the cities were at the same marginal rate of return (similar to equating the marginal utility per dollar).

Kerr et al. (2003) developed a case study on public expenditures in New Zealand to determine the public preferences for budget allocation among the different public services (e.g. health, education, environment, etc.). The case study was based on information collected through a large scale survey to determine public perceptions and preferences about the different services. Interestingly, the case study used the concept of marginal rate of substitution for budget reallocation among the different services, where the net marginal utility of spending on an item was calculated based on both the benefits obtained from spending on the item along with the disutility associated with having to pay higher taxes in order to fund that additional spending.

Al, et al. (2005) developed a model for allocating budgets among health care programs using a parameter called the cost-effectiveness ratio. If the costs-to-effects ratio of a given program is lower than a predefined “critical ratio” value, then the program will be selected and vice versa. This “critical ratio” represents the decision maker’s preferences among the different services (e.g. health, education, transit, etc.), and is calculated based on the marginal rate of substitution. Since the programs are allowed to be partially executed, the model tries to find the fractions of programs that optimize the decision within the available budget, resembling the conditions in consumer theory.

In the communication industry, Lin et al. (2009) investigated how to effectively allocate a “monetary budget” to meet each user’s physical power demand in a competitive “spectrum market”. The model developed was iterative and targeted to equalize the utilities of all users.

Ben-David and Tavor (2011) developed a model for optimum allocation of budgets using a social welfare function to maximize the social utility from different public goods under constrained budgets. The model used different weights to demonstrate the social utility gained from each supplied good. The weights were computed using different surveys by directly measuring consumer’s willingness to pay (WTP) for particular goods. The model constructed a demand curve for each public good and developed a method to optimally allocate budgets while maximizing consumer surplus. The model allocated budgets along with equalizing all products' marginal social benefit per marginal dollar spent, implying maximization of aggregate public utility.

Patidar, et al. (2007) tackled the concept of diminishing marginal utility in NCHRP report 590 to analyze, at the project-level, a set of alternative interventions for a given bridge asset using incremental comparison. It was found that the most costly intervention, the one with the highest additional increment of cost, would have lowest additional benefit relative to the penultimate competing alternative (with less cost) using the concept of diminishing marginal utility.

2.6 Behavioural Economics

Behavioural economics is the integration of psychological phenomena and behavioural aspects with economic reasoning (Humphrey, 1999). It has a great potential for application in infrastructure renewal decisions, as it challenges the basic assumption in classical economic models that decision makers are rational and always seeking utility maximization. Incorporating psychological aspects into economic decisions goes back to the 1870's during the neoclassical economics revolution, but soon lost its intellectual credibility in the 1930's when new consumer choice theories shifted the notion of utility from cardinal to ordinal preferences (Hands, 2010). More recently, however, the work of Daniel Kahneman, who is the 2002 Noble Prize laureate in economics sciences (Kahneman and Tversky, 2000; 1982), on psychological experiments, revived the theoretical foundations. Kahnman and Tversky's work asserted that decision makers are neither fully rational, nor wildly chaotic or completely irrational. Rather, decision makers follow their own "bounded rationality" which is characterized by systematic patterns of affection and cognition (Bolton, 2012; Selten, 1998). In the literature, various researchers (e.g., Gordon, 2013; Dawnay and Shah, 2005; Vossensteyn, 2005; Kahneman, 2003; Bolger and Antonides, 2000; etc.) discussed several behavioural aspects that can influence decision making. The main behavioural concepts have been summarized in Table 2.3.

Table 2.3 Main behavioural economics principles

Behaviour	Description
Influence of others	Individuals' behaviors/decisions are influenced by their peers
Gain versus Loss	Individuals react differently towards gain versus loss. For instance, if a problem is defined in the terms of loss, the results would differ from those obtained if it was defined in terms of gain (i.e., losing $100 versus gaining $100)
Recency effect	Individuals are biased towards their recent experience
Power of now	Individuals look for immediate gratification and are often biased towards short term gains (e.g., a consumer can buy a cheap fridge with high future operational costs rather than an expensive one with low future operational costs, the consumer may opt for the instant satisfaction)
Memory bias	Individuals' memory focuses more on past negative experiences
Diminishing marginal utility	An individual would appreciate the difference between $100 and $200 more than the difference between $1100 and $1200. Also, an individual gets higher satisfaction from first unit of consumption, then gets less marginal satisfaction from each additional unit
Pockets of money	Individuals tend to allocate budget to different categories (pockets) and do not like to exceed or mix the budgets in each
Choice architecture	Individuals with limited budget tend to avoid spending on very high (overly expensive) or very low (bad quality) choices
General	Individuals' self-expectations influence how they behave. People need to feel involved to make a change and are motivated to "do the right thing"

Recently, there has been a surge in research efforts that discussed the applicability of behavioural economics in various applications. Examples include capturing the "history effect" in software quality assessments to examine the influence of the experts' knowledge on the assessments (Hofman, 2011); and considering behavioral messiness in economic engineering (Bolton, 2012). In construction management, few efforts discussed behavioral or attitude-based issues. For example, Zhu (2008) discussed the rationality assumption in contract bidding theory. Runeson and Skitmore

(1999) pointed out that profit/utility maximization is unlikely to always be the goal of construction firms. Yousefi et al (2010) and Han et al. (2005) also developed attitude-based models for supporting multi-party negotiations and selection of international contracts, respectively. In an effort to incorporate behavioural aspects in infrastructure rehabilitation projects, this research examines the most common behaviour "loss-aversion", in Table 2.3, against the typical perspective of gain seeking and its impact on infrastructure fund-allocation decisions.

2.6.1 Gain versus Loss perspective

In behavioural economics, loss-aversion (which is usually associated with risk-taking) refers to people's tendency to strongly prefer avoiding loss rather than acquiring gain. This concept has been mostly tackled in the area of decision making under risk. For example, Tom, et al. (2007) studied the loss-aversion behaviour under risk using the traditional gambling case to figure out the reasons behind this behaviour. Gebhardt (2011) studied the loss-aversion behaviour of investors in decision-making regarding holding a risky asset or not, considering the physiological loss of consuming relatively less than the other investors. In construction as well, Campo (2012) studied the risk behaviour in bidding. However, this behaviour of loss-aversion has not been tackled in the infrastructure domain, particularly, infrastructure renewal funding decisions.

To demonstrate the difference between the loss and gain perspectives, an example from Tversky and Kahneman (1986) regarding preferences between two optional programs to fight a disease, is illustrated as shown in Figure 2.6. The example describes the choice of a group of survey participants between the two programs: A or B. To determine the impact of the participants' behaviour on their choice, the same information about the two programs were framed once in terms of gain (lives saved), and once in terms of loss (lives lost). From a gain framing perspective, adopting program A would result in saving 200 people with a chance of 100%, while adopting program B would result in saving 600 people (33% chance). From a loss framing perspective, on the other hand, adopting program A would result in losing 400 people (100% chance), while adopting program B is risky but has some chance of losing zero people. The survey results showed that when the problem was defined in terms of gain, 72% of the participants chose program A as it gives a guaranteed gain of saving 200 people. On the other hand, 78% of the survey participants chose program B when the problem was defined to them in terms of loss, as it avoids a guaranteed loss. Although both programs have equal expected utility of 200 lives saved (from the perspective of a rational decision-maker), this example shows that the behaviour of the decision maker towards gain and loss are not consistent. The decision maker towards gain is risk-averse, and towards loss is risk-taking. Thus, this problem shows the significant impact of framing variations on making decisions (Tversky and Kahneman, 1986). This problem of gain/loss closely resembles the situation of a municipality deciding between different funding strategies to improve the existing infrastructure assets. Thus, the change in the decision between the framing cases of loss versus gain, as in the illustrated example, makes it worthwhile to investigate these framing perspectives in the infrastructure fund-allocation domain.

In most of the literature related to optimum fund-allocation for rehabilitation purposes, the optimization targets to maximize the return (Gain or Utility) from the allocated money (e.g., Higgins and Harris, 2012; Marinon, et al., 2011; Irfan, et al., 2009; Moayyedi and Mason, 2004; Shohet and Perelstein, 2004). Thus, in this research different experiments are carried out on a real infrastructure case study to examine the influence of framing the infrastructure fund-allocation problem with respect to gain and with respect to loss on decisions, as discussed later in chapter 4.

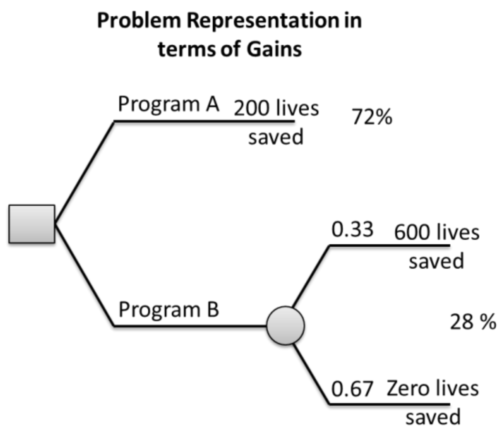
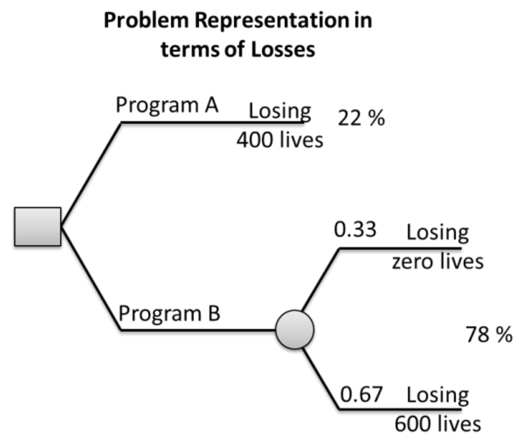
Problem description in terms of GAIN	Problem description in terms of LOSS
– Program A: provides guaranteed gain of 200 lives saved – Program B: Larger gain of 600 lives saved but has only 33% chance	– Program A: A sure loss of 400 lives – Program B: Risky but has a 67% chance of losing 600 lives
	

Figure 2.6 Impact of behaviours towards gain versus loss on decisions (based on Tversky and Kahneman, 1986).

2.7 Conclusion

This chapter has presented a review of the infrastructure fund-allocation problem along with a comprehensive review of the benefit-cost analysis (BCA) origins and the existing efforts in the infrastructure domain. Also a brief insight into the basic microeconomic principles that have potential application in the domain of infrastructure is presented. In addition, a brief introduction to the main concepts of behavioural economics has been discussed, and a detailed description of the loss-aversion behaviour, that has a potential in the infrastructure fund-allocation problem to examine the influence of framing the problem with respect to loss on the decisions. From the literature survey, the following has been noted:

- Many of the existing fund-allocation models dealt with the project- and network-level decisions independently;

- Benefit-cost analysis (BCA) that considers the return associated with each dollar spent has not been structured yet in the infrastructure rehabilitation problem to deal with a large portfolio of assets with multi-level decisions;
- Some efforts in the literature provided useful LCCA and optimization models to integrate both project- and network-level decisions, however, it is often difficult to interpret the results, and there is a lack of structured practical mechanisms to arrive at optimal fund-allocation solutions supported with solid economic justification;
- Microeconomic concepts (equal marginal utility per dollar and indifference curves) have the potential to explain and justify money spending, and visualize decisions. They can help reach an optimum solution by considering utility gained from money spent in the fund-allocation process. Therefore, these concepts have the potential to be adopted and tested in the infrastructure domain.
- None of the existing fund-allocation models incorporated behaviours to the funding process to reflect the different stakeholders' perceptions. In addition, they usually consider gain-seeking as the main behavioural framing perspective in formulating objectives; and
- Coordinating infrastructure renewal has a great potential for application as it can help reduce the disruption and the social costs associated with rehabilitation work.

Chapter 3

Case Studies and Mathematical Optimization Models

3.1 Introduction

This chapter describes two case studies of two different networks of assets with different characteristics; one relates to building components, and one relates to a network of roads. Both case studies will be used in later chapters to examine the proposed methods in this research. The chapter describes, as well, a general mathematical optimization model and its implementation on both case studies to determine global optimum solutions for the purpose of investigating the level of complexity associated with them, to validate the applicability of microeconomic concepts in the infrastructure domain, and to affirm the quality of the solutions provided by the proposed heuristic method in the later chapters.

3.2 Case Study I: School Buildings

This case study investigates the rehabilitation of a network of 800 building components that were obtained from the Toronto District School Board (TDSB). The building components are part of a bi-level building hierarchy: system-level categories (541 architectural, 210 mechanical, and 49 electrical assets); and component-level categories. At the component-level, the architectural assets in the case study data involve windows, and roofs; mechanical assets involve HVACs and boilers; and electrical assets involve fire alarm systems. The planning horizon is assumed 5 years (tactical plan, however, the LCCA model is flexible to consider any length or cycles of funding periods) and the available budget for rehabilitation is assumed $10 million a year with an assumed interest rate of 6%.

The case study was reported in Hegazy and Elhakeem (2011) where a detailed LCCA was performed following the stages previously described in Figure 2.1 (Chapter 2). The data available include operational costs, inspected conditions, deterioration patterns of components, renewal strategies, etc. The asset condition is represented in terms of a deterioration index DI (scaled from 0 to 100), which is function of the severity of the inspected defect and its weight (ElHakeem and Hegazy, 2012), as follows:

$$DI = \frac{\sum_{i=1}^{d} W_i \times S_i}{100} \tag{3.1}$$

Where, S_i is the inspected severity for defect i, on a scale from 0 to 100, and W_i is the relative weight of each defect to reflect its impact on the overall condition of the component. The complete list of defects and their weights for all building components were obtained from the Toronto District School Board (TDSB), with their weights were determined through surveys among experienced building inspectors and operators at the TDSB (ElHakeem and Hegazy, 2012). A DI value of 0 implies excellent condition (no deterioration), while a DI of 100 implies an extremely critical condition (maximum deterioration). Customized deterioration patterns for each component were generated using Markov-Chain model (Elhakeem and Hegazy, 2005). These patterns were used to predict the future DIs in the next 5 years (the selected planning horizon). The objective in this case study is to improve the condition of the overall network by deciding on which components to be funded (network-level decision) using which rehabilitation strategy (project-level decision) in each year within the planning horizon while meeting the budget constraints.

3.2.1 Life Cycle Cost Analysis (LCCA)

In this case study, the number of assets is 800, each with 3 possible rehabilitation options, and 5 possible rehabilitation years or no rehabilitation, thus the solution space for such problem is huge. Therefore, to optimize decisions considering both project-and network-levels, and to reduce the solution space, a structured segmentation approach is followed where the optimization is done one year at a time at both levels. This approach is built upon the Multiple Optimization and Segmentation Technique (MOST) of Hegazy and Elhakeem (2011) that includes both project- and network-level life cycle cost analyses (LCCA) for multi-year planning horizons. A schematic of the components of MOST and its adaptation in this research is shown in Figure 3.1. In MOST, project-level analysis is done first through small individual optimizations for each asset to determine the best rehabilitation method assuming the rehabilitation year will be in year 1, year 2, etc., (right side of Figure 3.1).

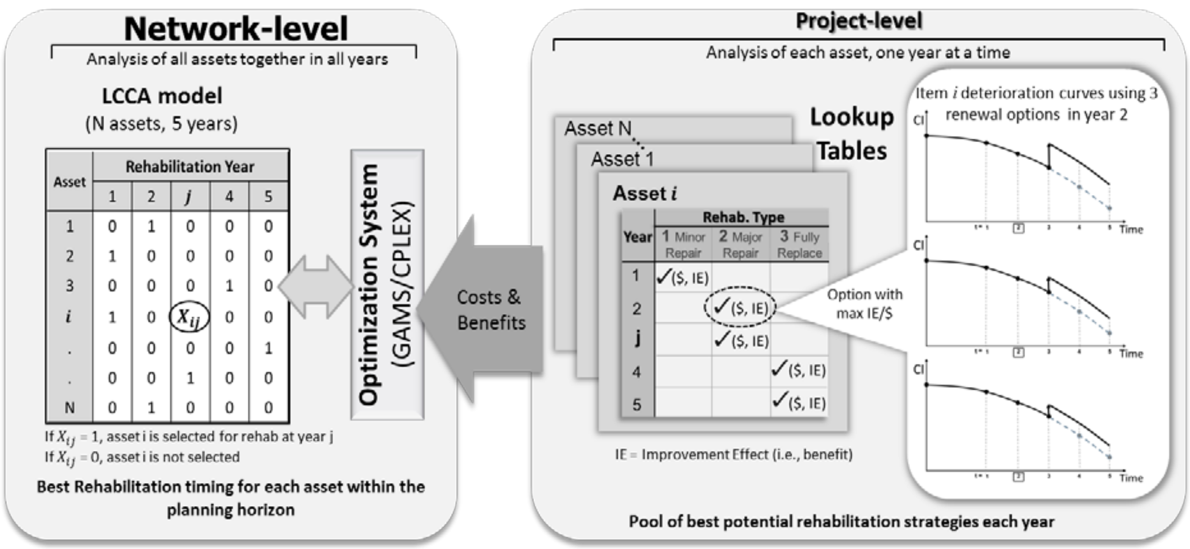


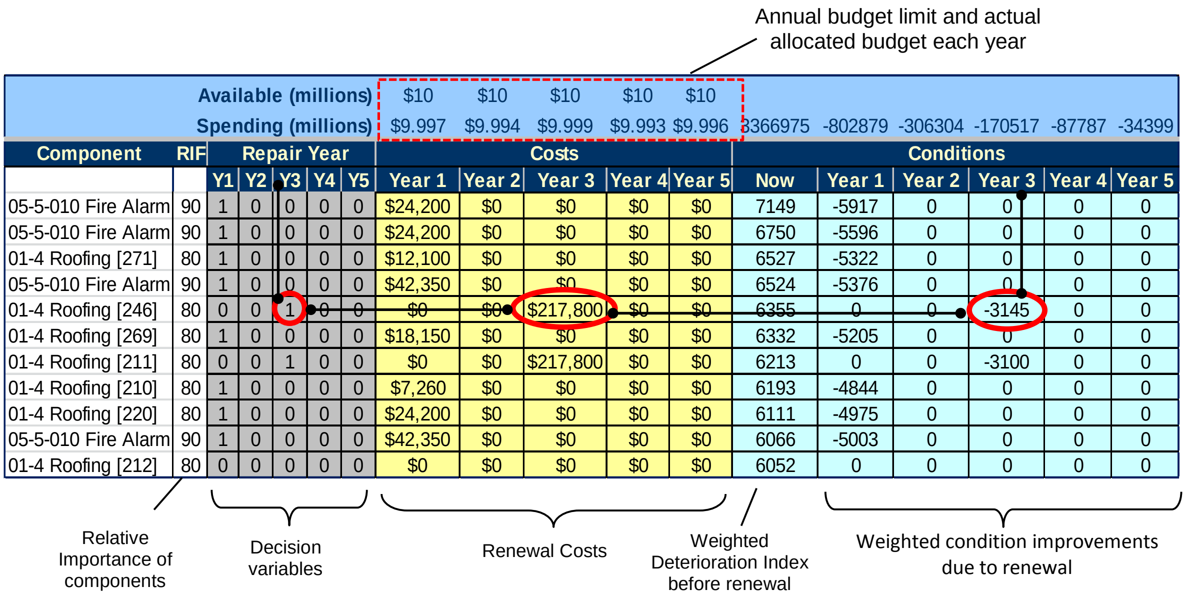
Figure 3.1 Schematic of MOST and its adaptation to the network-level fund allocation model

Each small optimization considers one asset *i*, and the impact of the different rehabilitation options (e.g., minor, major, or full replacement) in a certain year *j* on its deterioration behaviour. The optimization then selects one of these options that maximizes the benefit-cost ratio in this repair year *j*. This process is repeated for each year j for a given asset *i* within the planning horizon, thus ending up with the best rehabilitation methods in each year. These project-level optimizations result in a pool of best potential rehabilitation strategies along with the associated benefits/improvements and costs for all assets in any year in the planning horizon. This pool is used as lookup input tables to facilitate the network-level analysis.

At the network-level also, the segmentation technique divides the problem into yearly smaller-size optimizations (facilitated only by the pre-analysis at the project-level). The optimization at each year determines which asset to select for that year (binary decision) along with the costs and the improvements retrieved from the lookup tables. The LCCA model was implemented on MS Excel and has all the formulations that link the renewal cost and condition improvement with the decision variables for each component (marked row in Figure 3.2). In MOST, the network-level optimization model was implemented using genetic algorithms with utility maximization as an objective function (Hegazy and ElHakeem, 2011).

In this research, however, the optimization is implemented using an advanced mathematical optimization tool, General Algebraic Modeling System (GAMS), as shown in the left side of Figure 3.1, which consists of an array of integrated high-performance built-in solvers. CPLEX internal solver (IBM-ILOG, 2009), a powerful mathematical optimization solver, is used in this model as it uses advanced algorithms including branch and bound and a variety of cutting plane strategies and node-selection strategies to solve optimization problems (Patidar, et al., 2007). It suits as well a variety of optimization problems, including mixed-integer programming problems, and is suitable to model large-scale optimization problems. The details of the optimization model and the formulations are discussed in the next subsection.

The optimization model has been formulated in the form of a linear optimization model that considers the 5 years planning horizon in one-shot rather than year-by-year optimization to avoid complexities behind updating the solution space in every subsequent year after removing the assets that have been selected in the preceding year (Rashedi and Hegazy, 2014).



							Available (millions)	$10	$10	$10	$10	$10						
							Spending (millions)	$9.997	$9.994	$9.999	$9.993	$9.996	3366975	-802879	-306304	-170517	-87787	-34399
Component	RIF	Repair Year						Costs					Conditions					
		Y1	Y2	Y3	Y4	Y5		Year 1	Year 2	Year 3	Year 4	Year 5	Now	Year 1	Year 2	Year 3	Year 4	Year 5
05-5-010 Fire Alarm	90	1	0	0	0	0		$24,200	$0	$0	$0	$0	7149	-5917	0	0	0	0
05-5-010 Fire Alarm	90	1	0	0	0	0		$24,200	$0	$0	$0	$0	6750	-5596	0	0	0	0
01-4 Roofing [271]	80	1	0	0	0	0		$12,100	$0	$0	$0	$0	6527	-5322	0	0	0	0
05-5-010 Fire Alarm	90	1	0	0	0	0		$42,350	$0	$0	$0	$0	6524	-5376	0	0	0	0
01-4 Roofing [246]	80	0	0	1	0	0		$0	$0	$217,800	$0	$0	6355	0	0	-3145	0	0
01-4 Roofing [269]	80	1	0	0	0	0		$18,150	$0	$0	$0	$0	6332	-5205	0	0	0	0
01-4 Roofing [211]	80	0	0	1	0	0		$0	$0	$217,800	$0	$0	6213	0	0	-3100	0	0
01-4 Roofing [210]	80	1	0	0	0	0		$7,260	$0	$0	$0	$0	6193	-4844	0	0	0	0
01-4 Roofing [220]	80	1	0	0	0	0		$24,200	$0	$0	$0	$0	6111	-4975	0	0	0	0
05-5-010 Fire Alarm	90	1	0	0	0	0		$42,350	$0	$0	$0	$0	6066	-5003	0	0	0	0
01-4 Roofing [212]	80	0	0	0	0	0		$0	$0	$0	$0	$0	6052	0	0	0	0	0

Figure 3.2 LCCA model for the building case study

3.2.2 Network-level Optimization Model and Formulations

The optimization model is designed to be generic enough to accommodate any type of data. The model's objective function is to maximize the overall network condition index CI_N, which is an aggregation of one or more performance parameters of all individual assets. The life cycle analysis uses a planning horizon of 5 years. Therefore, each asset can be selected in year 1, 2…, 5, or zero (no action). A Binary decision variable X_{ij} is used to represent the 2-dimensional solution space of N-assets and 5 years as shown in Equation 3.2. If X_{ij} for a certain asset i and year j is equal to 1, then the asset is selected for rehabilitation at this year, and the associated rehabilitation cost and benefit would be retrieved from the appropriate lookup tables. The model's variables, constraints, and objective function are as follows:

Decision Variables:
(Matrix of rehabilitation timing decisions)

$$\begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} \\ . & . & . & . & . \\ . & . & X_{ij} & . & . \\ . & . & . & . & . \\ X_{N1} & X_{N2} & X_{N3} & X_{N4} & X_{N5} \end{bmatrix} \quad (3.2)$$

Where, if X_{ij}= 1, then asset (*i*) is selected for rehabilitation in year (*j*), otherwise X_{ij}= 0 and the asset is not selected.

Objective function: is set to maximize the network overall condition index (CI_N), which is the weighted sum of all assets' condition after adding the improvement effects of each asset *i* selected for rehabilitation within the planning horizon, as follows:

$$\text{Maximize } CI_N = \left[\begin{array}{c} \text{weighted sum of assets'} \\ \text{conditions without repair} \end{array} \right] + \left[\begin{array}{c} \text{weighted sum of assets'} \\ \text{improvements due to repair} \end{array} \right]$$

$$= \frac{\sum_i (AC_{i0} \times RIF_i)}{\sum_i RIF_i} + \frac{\sum_i [\sum_j (IE_{ij} \times X_{ij}) \times RIF_i]}{\sum_i RIF_i} \quad (3.3)$$

Where, RIF_i is the relative importance factor of each asset *i*, which is used to capture the decision maker's preferences in differentiating the importance of different asset categories (e.g., boiler vs. window vs. roof). IE_{ij} is the improvement effect that each asset *i*, selected for rehabilitation in year *j*, adds to the whole network. The improvement effect IE_{ij}, as shown in Figure 3.3, is computed as follows:

$$IE_{ij} = [AC_{ij} - AC_{i0}] \quad , t = 1, 2, 3, 4, 5 \tag{3.4}$$

$$AC_{ij} = (\sum_{t=1}^{5} CI_{ij}^{t})/6 \tag{3.5}$$

$$AC_{i0} = (\sum_{t=1}^{5} CI_{i0}^{t})/5 \tag{3.6}$$

Where, AC_{ij} is the average of condition indexes CI_{ij}^{t} s of asset (*i*) in all years (*t* = 1, 2, 3, 4, 5) when rehabilitation is decided in year *j* (as shown in Figure 3.3 for *j* = 3); while AC_{i0} is the average of CI_{i0}^{t}s for the asset (*i*) in all years (*t* = 1, 2, 3, 4, 5) in case of no rehabilitation (*j* = 0, as shown in Figure 3.3). For the case described in Figure 3.3, the average condition without rehabilitation, AC_{i0} = (90+75+65+45+25) / 5 = 60, while the average condition due to rehabilitation, AC_{i3} becomes = (90+75+65+90+70+50)/ 6 = 73.3. As such, the improvement effect (IE_{i3}) according to Equation 3.4 becomes = 73.3 - 60 = 13.3.

Constraint(s): The total rehabilitation cost (TC_j), which is the sum of all assets' costs (RC_{ij}) in any year *j*, should not exceed the available budget for that year, as shown in Equation 3.7. Also, each asset can only be selected once for rehabilitation within the planning horizon or not selected, as shown in Equation 3.7.

$$TC_j = \sum_i (RC_{ij} * X_{ij}) \le B_j \tag{3.7}$$

$$(\sum_j X_{ij}) \le 1 \tag{3.8}$$

This generic optimization model has been applied to the building case study data (Rashedi, 2011), however, the parameters in the generic Equations 3.3, 3.3, 3.4 and 3.6 were modified to consider the component deterioration index (DI_{ij}^{t}) rather than CI_{ij}^{t} as a measure of the asset condition. In this case study, the components' relative importance factors (RIF) values range from 100 to 0, where a value of 100 implies extremely important, and a value of 0 implies least important, and they reflect the component's impact on safety, functionality, and other components. The higher the *RIF* value of a component, the higher the need to repair the component. The *RIFs* were determined through surveys among experienced building inspectors and operators at the Toronto District School Board (TDSB) (Elhakeem and Hegazy, 2005). The objective function has been adjusted to minimize the overall CI_N of the network, as lower values of *DI* indicate better condition.

3.2.3 Optimization Results

Figure 3.4 shows the code and the optimum result of GAMS. The model reached a near-optimum solution value of 31.71 for the network overall condition index CI_N, which represents a large improvement from the original CI_N value of 54.15 without rehabilitation. The resulting values of the decision variables X_{ij} were determined in binary format. Those values were exported to the LCCA Excel spreadsheet to perform further analysis. 541 out of the 800 building components were selected in total for renewal. These results will be further analyzed with respect to the microeconomic concept of equal marginal utility per dollar in Chapter 4 to test whether an equilibrium was maintained across the assets or not. Also they will be used later in Chapter 5 to compare against the results obtained using the proposed heuristic method in this research, and thus validate the quality of the solutions provided.

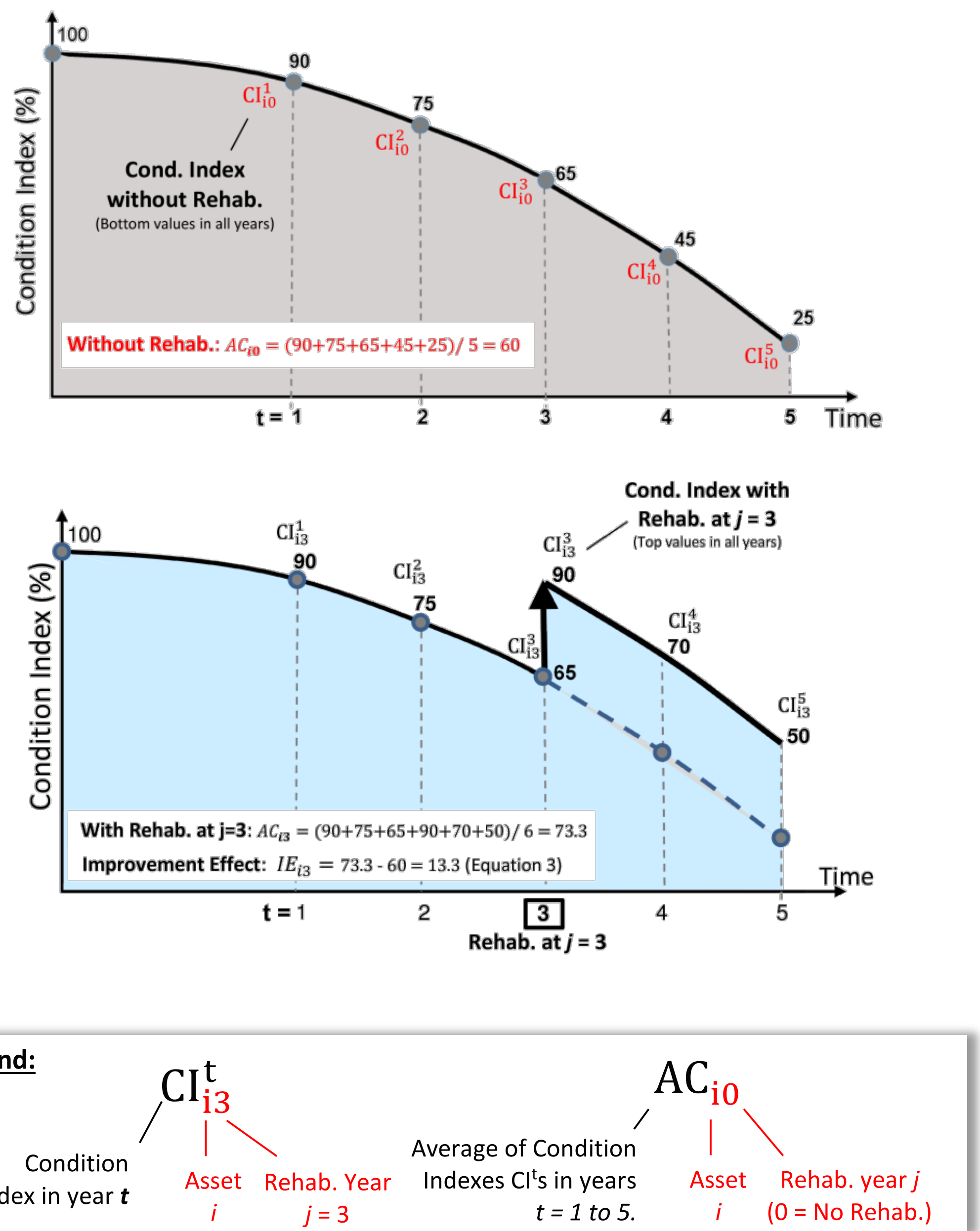


Figure 3.3 Schematic of the Improvement Effect (IE) calculation due to rehabilitation

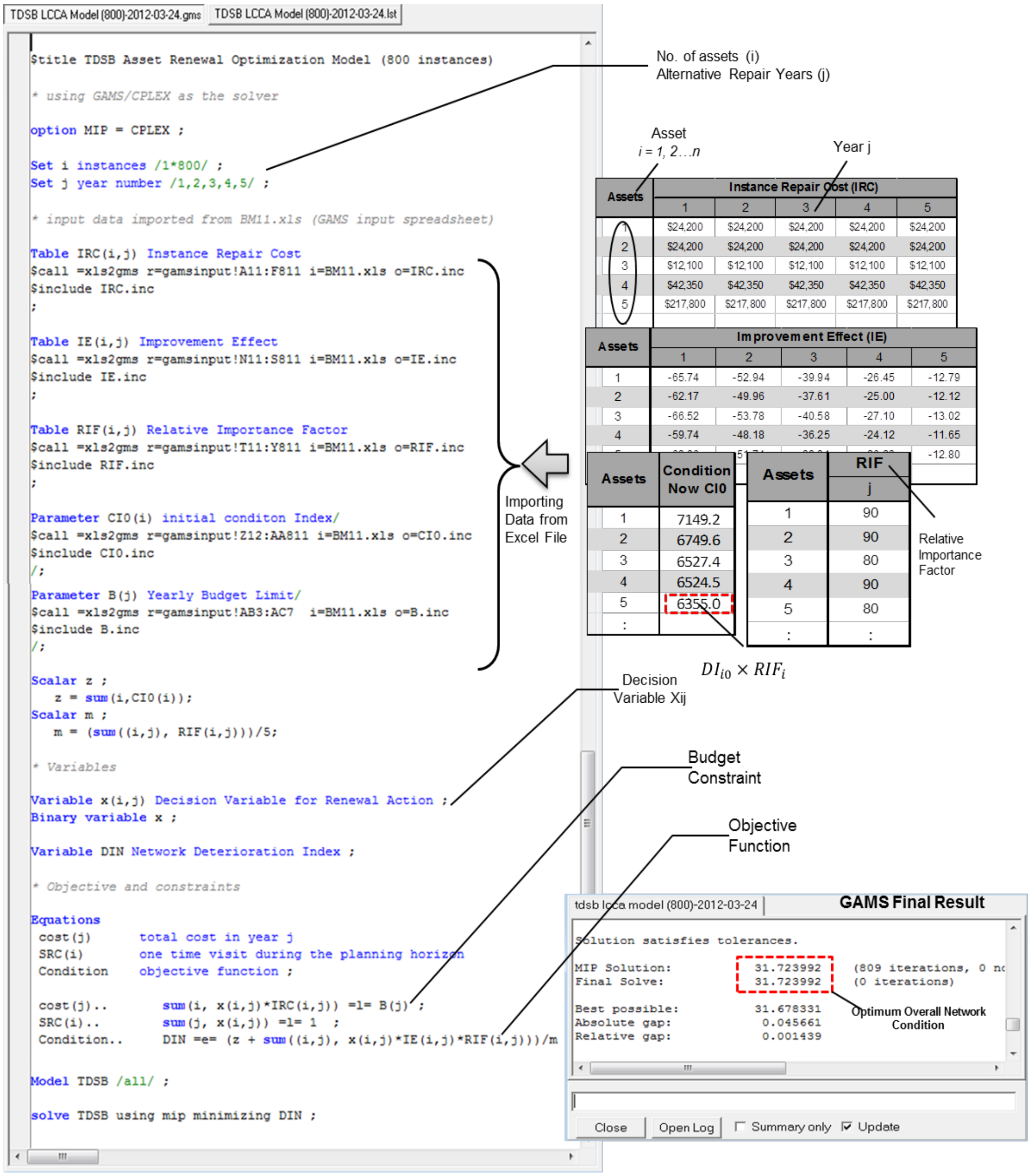


Figure 3.4 GAMS Code for Network-level optimization-Case Study I

3.3 Case Study II: Pavement Network

This case study is a pavement network which was part of an asset management challenge posted at the 7th International Conference on Managing Pavements (Haas, 2008), as shown in Appendix II. The pavement network consists of a total of 1293 road sections of two types: interurban and rural roads. The annual budget is assumed to be $10 million dollars with an annual interest rate of 6%. The planning horizon is assumed 5 years (tactical plan, however, the LCCA model is flexible to consider any length or cycles of funding periods). The information given on each road section includes: length, width, Annual Average Daily Traffic (AADT), year of construction, and surface condition assessments (International Roughness Index, IRI, and others). The condition of a given pavement is measured in terms of its IRI as a single parameter that represents pavement performance, where the lower the value, the better the condition. Other general information was also given, as shown in Tables 3.1, 3.2, and 3.3, regarding the annual rate of IRI increase (deterioration rate), the max allowed IRI values (trigger levels), and the unit cost of five types of treatments, respectively. In an effort to capture the importance of the different asset categories, the trigger values have been used to determine the relative importance factor (RIF) of each road section (RIF = maximum IRI –IRI trigger value). For example, if a road has AADT greater than 8000, then IRI should be maintained at a value equal or less than 1.9 (from Table 3.2), and accordingly, the RIF is calculated as 2.1 (i.e., 4 – IRI).

Table 3.1 Relative importance factors

AADT	IRI Trigger Value (mm/m)	Rel. Importance Factor (RIF)
<400	3.0	1.0
400-1500	2.6	1.4
1500-6000	2.3	1.7
6000-8000	2.1	1.9
>8000	1.9	2.1

Table 3.2 Rate of increase of IRI

Road Class	AADT	Rate of Increase in IRI (m/km/yr)
Interurban	> 8000	0.069
	< 8000	0.077
Rural	> 1500	0.091
	< 1500	0.101

Table 3.3 Unit cost of treatments

Intervention Type	Cost ($)
1. Preventive Maintenance	6.45
2. 40mm Overlay	6.75
3. Cold Mill & 40mm Overlay	10.50
4. 75mm Overlay	15.75
5. 100mm Overlay	16.50

The charts in Figure 3.5 provide the IRI improvement due to the five pavement treatments of Table 3.3, as a function of the road type, which is necessary for life cycle cost analysis. The case study data was put in an Excel spreadsheet with each pavement section in a row. The spreadsheet was then extended with equations that incorporate all the relations in Tables 3.1, 3.2, and 3.3, as well as Figure 3.5 to formulate a detailed LCCA analysis, incorporating deterioration patterns, repair decisions, cost calculations, IRI improvement, users' vehicle operating costs (VOC), and accumulated yearly expenditures. Having this information about the pavement network, the previously described general network-level optimization model (subsection 3.2.2) was applied to the case study data. First, project-level analysis was carried out separately using Benefit-cost-ratio analysis following the MOST technique of Hegazy and Elhakeem (2011), as previously described for Case study I (subsection 3.2.1). The project-level results and all the necessary data were then exported as an input file to the GAMS Model to conduct the network-level optimization. Since the condition of a given pavement is defined in terms of a single parameter (the International Roughness Index, IRI), thus all the parameters in the generic Equations 3.2, 3.3, 3.4 and 3.5

(e.g., CI_N, IE_{ij}, AC_{ij}) were modified to consider IRI_{ij}^t as the measure of the asset condition rather than CI_{ij}^t. Also the objective function in Equation 3.5 was adjusted to minimize the overall CI_N of the network, as lower values of IRI indicate better condition.

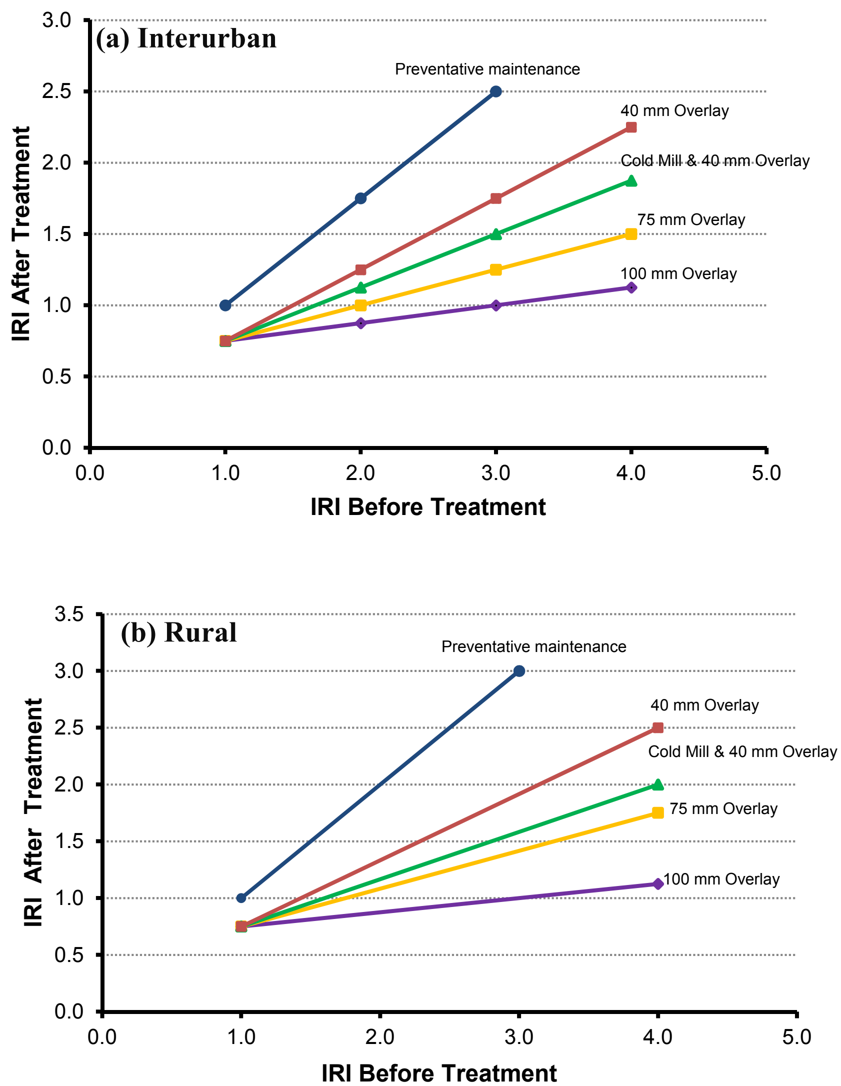


Figure 3.5 IRI charts before and after treatment: (a) interurban roads; and (b) rural roads (based on Haas, 2008)

In this case study, the objective function is multiplied by an additional Size Factor (SF_i) to take into consideration the differences in the road sections' areas, as shown in Equation 3.9. The factor is scaled from 1 to 10, where 10 is for the largest road section area, and 1 is for the smallest road section area. After applying GAMS optimization model, the optimum rehabilitation year of each road section was determined and the overall network condition was maximized, under an annual budget limit of $10 Million.

$$SF_i = 10 - \frac{[Road\ Area(Max) - Road\ Area(asset_i)] \times (10 - 1)}{[Road\ Area(Max) - Road\ Area(Min)]} \tag{3.9}$$

3.3.1 Optimization Results

The optimization model reached a near-optimum solution of 1.42 for the overall network CI_N, which represents a good improvement from a CI_N value of 1.7 without any rehabilitation. To perform further analysis, the resulting values of the binary decision variables X_{ij} were exported to the LCCA Excel spreadsheet as shown in Figure 3.6, which depicts as well a sample of the coding and the formulations in GAMS modelling environment. According to the analysis, 688 (196 interurban, and 492 rural) road sections out of the 1293 total road sections existing in the network were selected for renewal.

To validate the applicability of the microeconomic concepts in the infrastructure domain, those results obtained from the mathematical optimization model for both the building and the pavement case studies will be analyzed, in Chapter 4, with respect to the concept of equal marginal utility per dollar to examine whether this concept is maintained across the optimization results or not.

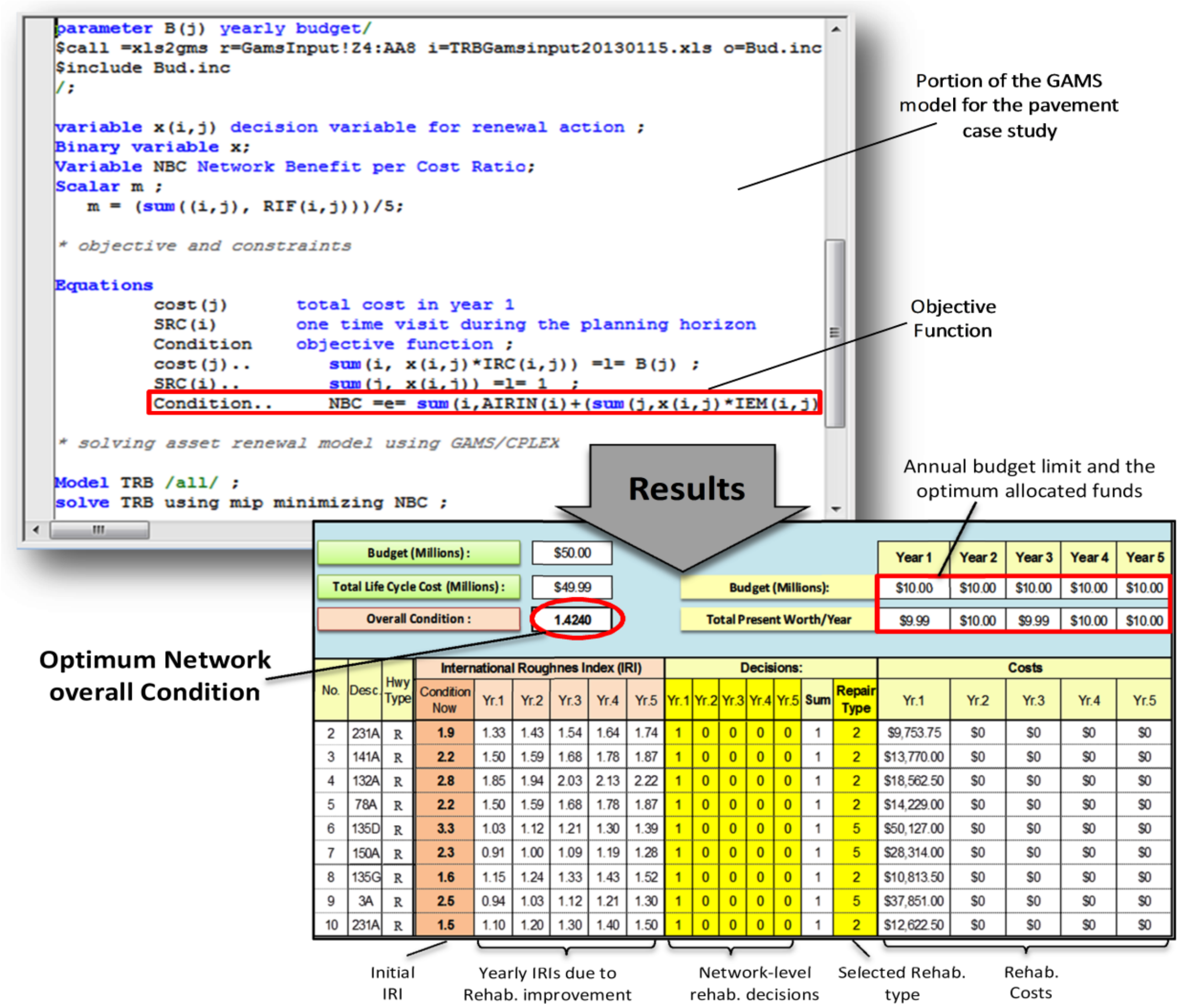


Figure 3.6 Network-level optimization model and results for Case Study II

3.4 Conclusion

In this chapter, LCCA, project-level and Network-level analyses have been presented for two case studies of different number of assets and different level of decisions. This research focuses on the network-level of decisions while building upon a readily developed project-level model using Benefit-cost ratio analysis of Hegazy and ElHakeem (2011). Accordingly, a general network-level mathematical optimization model has been developed for both case studies. This general model proved, in both case studies, to work very well and can consider thousands of assets at the same time, without performance degradation, which is a problem facing other evolutionary optimization tools such as genetic algorithms. GAMS/CPLEX tool proved to work extremely well and took less than one minute to produce optimum results. Despite the good performance of the mathematical optimization model, it is a black box where the results are difficult to be explained or justified. Also the model's formulations were framed from the gain perspective considering single point of view. Therefore, in the next chapters, different perspectives are proposed to overcome the mentioned drawbacks in order to provide fund-allocation decisions supported with solid economic justification while considering the different stakeholders preferences. Also, the solutions obtained by the optimization model for both case studies will be used in the later chapters to test the applicability of the adopted economic theories and to affirm the quality of the solutions provided by the proposed enhanced benefit-cost analysis (EBCA) heuristic approach in this research.

Chapter 4

Economic Perspective to Infrastructure Fund-Allocation

4.1 Introduction

In order to provide better justification for infrastructure fund-allocation decisions, this chapter examines the applicability of microeconomic concepts in the infrastructure domain. It tests the optimum decisions obtained using mathematical optimization for the case studies in Chapter 3, with respect to the concept of equal marginal utility per dollar. Later in Chapter 5, the consumer theory concept of indifference maps will be examined in the infrastructure problem. This chapter also investigates the influence of behaviours, specifically "Loss-aversion", on funding decisions by comparing the traditional strategy of maximizing gain against the strategy of minimizing loss due to delaying or not repairing assets from the perspective of different stakeholders.

4.2 Microeconomics in the Infrastructure Domain

While the existing efforts in the literature provided useful LCCA models, there is a lack of satisfactory optimization results for large scale rehabilitation problems. Moreover, they suffer from many drawbacks, such as the difficulty that the decision maker has in formulating complex functions and constraints. In addition, optimization is often looked at by many industry professionals as a black box that lacks economic reasoning to support rehabilitation decisions as most of them are random-based combinatorial techniques, to determine the optimum combination of rehabilitation years and repair strategies for all assets. Also, there is a lack of methods and tools for testing the quality of LCCA models and for providing sound economic justification behind fund-allocation decisions. Therefore, this research aims at improving fund-allocation practices for infrastructure rehabilitation by exporting microeconomic concepts that has been studied extensively over the past 200 years in the science of Microeconomics to the infrastructure domain to help provide wiser spending of tax-payers' money.

The basic premise of this research, as shown in Figure 4.1, is the analogy between the consumer's problem of spending money among different expenditure categories under limited income, and the infrastructure decision problem of allocating limited funds, from tax payers' money, among different asset categories. To affirm the applicability of utilizing microeconomic concepts in the infrastructure domain, a microeconomic analysis has been performed on the optimum funding solutions of the building and pavement case studies, obtained using the mathematical optimization model in Chapter 3, with respect to the law of equi-marginal utility per dollar.

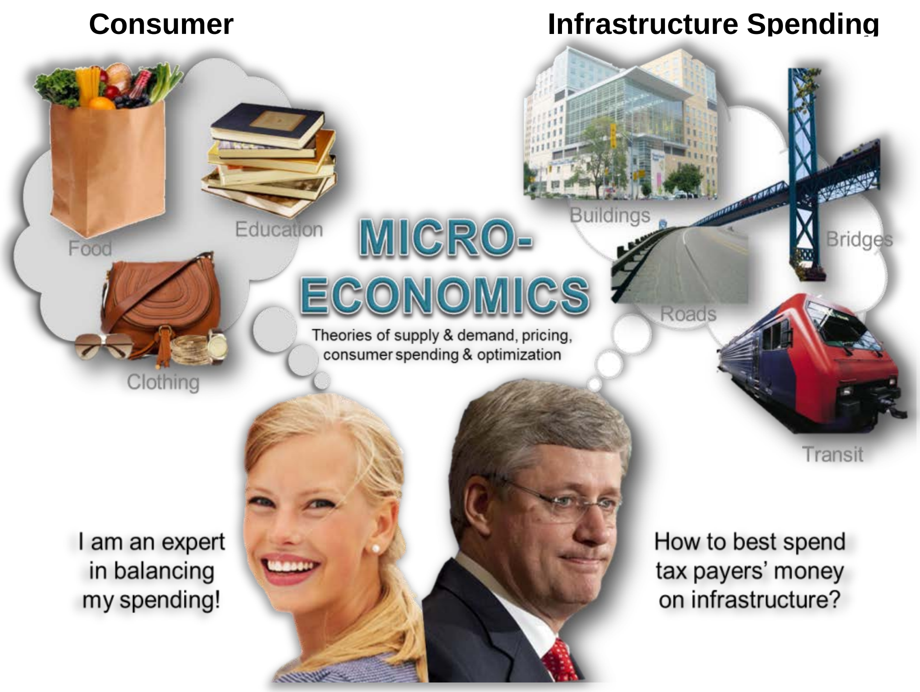


Figure 4.1 Analogy between the consumer spending and infrastructure spending

4.2.1 Microeconomic Benchmark Mechanism for Infrastructure Funding Decisions

In the microeconomic literature, the law of equal marginal utility per dollar has been proven, as previously discussed in chapter 2, to arrive at optimum allocation of a limited fund by targeting equilibrium (equality) among the marginal utility per dollar spent on the different expenditure categories, rather than the typical maximization of benefits or minimization of costs. As such, optimum fund-allocation is represented by an equilibrium state at which the following relationship holds:

$$\left(\frac{MU}{\$}\right)_{xth} = \left(\frac{MU}{\$}\right)_{yth} \tag{4.1}$$

Where, x^{th} and y^{th} are the last units to be selected from each category. Therefore, in each case study, the marginal utility per dollar spent on rehabilitating the last selected asset from each asset category at any funding year was computed to check the equality of values using equation (4.1), and thus check whether the concept is maintained across the different asset categories or not. Figure 4.2 shows a schematic diagram of the microeconomic analysis process that involves the following generic steps:

- Export the optimum results obtained using any fund-allocation mechanism to a spreadsheet
- For each funding year in the analysis:
    - Consider only the assets that were selected for funding in this year;
    - Group the selected assets according to their category (e.g., interurban, and rural);
    - Calculate the marginal utility (MU/$) for each asset;
    - Sort the assets in each category in a descending order according to (MU/$); and
    - Examine the equality of the (MU/$) values (Equation 4.1) among the last assets selected for funding in each category.

– Proceed to step 2 for the analysis of next year, until the end of the predefined planning horizon.

In the consumer theory, the marginal utility (MU) is the additional utility that each additional unit of consumption from a given product adds to the consumer's satisfaction. In this microeconomic analysis of the fund-allocation decisions, the marginal utility (MU) is the weighted condition improvement effect (IE) that each asset adds to the overall network condition. Also, the cost of purchasing one unit from a product in the consumer theory is the cost of repairing/rehabilitating (RC) one asset from an asset category in a given network of assets. Accordingly, the marginal utility per dollar associated with rehabilitating a given asset *i* in year *j* is computed as follows:

Marginal Utility of an asset *i* in year *j* $(MU_{ij}) = IE_{ij} \times RIF_i$ (4.2)

Marginal Utility per dollar (MU/$) = MU_{ij} / RC_{ij} (4.3)

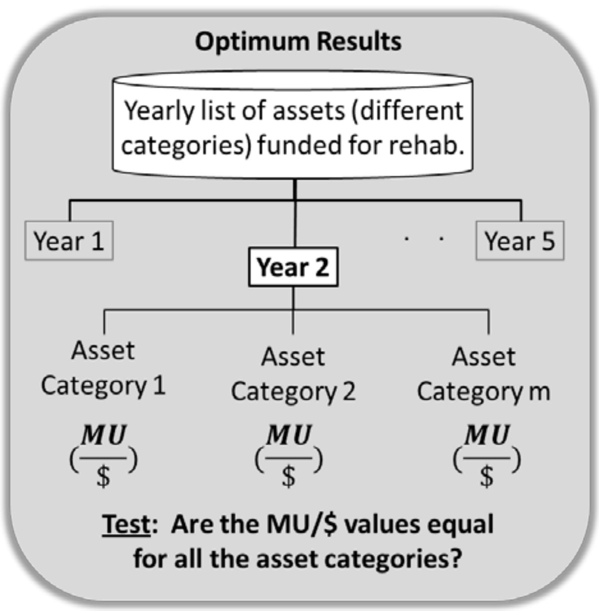


Figure 4.2 Schematic of the Microeconomic analysis of optimum fund-allocation results

4.2.2 Microeconomic Analysis: Building Case Study

Using the developed LCCA and optimization models in Chapter 3, and following the microeconomic analysis generic steps, the selected building components by GAMS for funding in each year were grouped according to their asset categories, and the MU/$ of each component is calculated using Equations 4.2 and 4.3. The Improvement Effect (IE), in this case study, is function of the asset's deterioration index (DI). The analysis of the optimum fund-allocation decisions in each year is carried out at two levels: system-level (Arch., Mech., and Elec.); and component-level (Roofs, Windows, Boilers, and Fire Alarm System). Figure 4.3 is showing the application of the generic microeconomic analysis of Figure 4.2 to the optimum fund-allocation decisions in year 4 where only architectural and mechanical assets were competing for funding at the system-level of decisions. The figure is demonstrating, as well, the implementation of the analysis in a way that resembles the consumer problem, previously discussed in Chapter 2. The top part of the figure shows the consumer example (Product X and Y) and the optimum solution achieved by equating the MU/$ of both product categories. Similarly, the bottom part of the figure shows the optimum decision that equates the MU/$ (condition improvement per dollar) across architectural and mechanical asset categories, and almost exhausts the available $10 million budget. Starting from the left of the figure, each column in the building assets case study resembles the corresponding column in the X-Y consumer example. For instance, the component renewal cost resembles the product unit price, and the condition improvement that each asset adds to the network resembles the utility that each additional unit of a product adds. Accordingly, the assets are sorted in a descending order according to the MU/$ to resemble the diminishing marginal utility per dollar of the consumer theory. The optimum combination in the X-Y consumer example was a combination of 6 X units and 2 Y units at equal MU/$ =5 and fully consumes the $40 available budget. Similarly, the optimum combination in the building case at year 4 is 45 architectural and 22 mechanical assets, at almost equal MU/$, with total cost of $9.99M that almost fully consumes the $10 million available budget.

Product X Vs. **Product Y**

Quantity	Unit Cost	MU	MU/$	Total Cost	Quantity	Unit Cost	MU	MU/$	Total Cost
10	$4	5	1.25	$40	0	$0	0	0	0
8	$4	10	2.50	$32	1	$8	50	6.25	$8
6	$4	20	5.00	$24	2	$8	40	5.00	$16
4	$4	24	6.00	$16	3	$8	32	4.00	$24

Best decision:
6 X units + 2 Y units
at equal MU/$ of 5
with $40 spending

Architectural Vs. **Mechanical**

Comp. No.	Component Renewal Cost ($)	Condition Improvement (MU)	MU/$	Cum. Cost
1	$30,250	539.59	0.018	$30,250
2	$30,250	506.08	0.017	$60,500
3	$36,300	534.72	0.015	$96,800
:	:	:	:	:
45	$90,750	754.83	0.008	$6,478,300

Comp. No.	Component Renewal Cost ($)	Condition Improvement (MU)	MU/$	Cum. Cost
1	$145,200	1352.78	0.0093	$145,200
2	$181,500	1646.54	0.0091	$326,700
3	$193,600	1717.43	0.0089	$520,300
:	:	:	:	:
22	$96,800	642.6	0.007	$3,515,050

Figure 4.3 Mapping the consumer-theory example to building renewals in year 4

Tables 4.1 and 4.2 provide a summary of the analysis at both decision levels, showing for each year: the total number of assets selected in each funding year; the number of assets from each category selected for funding; and the MU/$ value of the last asset selected for funding in each category of assets. From the analysis at both decision levels (system- and component-level), it has been noticed that the MU/$ values are very close in each year of the planning horizon. For example, at the system-level in year 3, the optimum number of assets selected for funding is 87 (56 architectural, 31 mechanical, and zero electrical assets). The MU/$ spent on the last asset selected for rehabilitation in the architectural, and mechanical categories are 0.014 and 0.013, respectively as shown in Table 4.1, which are very close. Similarly for the component-level, the values are very close in each year of the planning horizon. Thus, the analysis has proved that the concept of equal marginal utility per dollar is maintained across the different asset categories, at both levels.

Table 4.1 System-level microeconomic analysis of building case optimal results

	Year 1		Year 2		Year 3		Year 4		Year 5	
	No.	**MU/$**	**No.**	**MU/$**	**No.**	**MU/$**	**No.**	**MU/$**	**No.**	**MU/$**
Architectural assets	122	0.043	49	0.027	56	0.014	45	0.008	33	0.003
Mechanical assets	56	0.043	60	0.013	31	0.013	22	0.007	18	0.003
Electrical assets	43	0.043	6	0.026						
Total	221		115		87		67		51	

Table 4.2 Component-level microeconomic analysis of building case optimal results

	Year 1		Year 2		Year 3		Year 4		Year 5	
	No.	**MU/$**	**No.**	**MU/$**	**No.**	**MU/$**	**No.**	**MU/$**	**No.**	**MU/$**
Windows	75	0.043	17	0.027	21	0.014	21	0.008	15	0.003
Roofs	47	0.05	32	0.027	35	0.015	24	0.008	18	0.003
Boilers	56	0.043	60	0.013	31	0.013	22	0.007	18	0.003
Fire Alarm	43	0.043	6	0.026	-	-	-	-	-	-
Total	221		115		87		67		51	

4.2.3 Microeconomic Analysis: Pavement Case Study

Similarly to the building case study, the optimum results obtained by GAMS in the pavement case study in Chapter 3, were analyzed with respect to the law of equi-marginal utility per dollar. Using Equations 4.2 and 4.3, MU/$ values were calculated for each pavement section with the Improvement Effect (IE) being a function of the International Roughness Index (IRI) rather than deterioration index (DI) in the building case study. The improvement effect, in this case study, is multiplied by a Size Factor (SF) as well to take into consideration the differences in the road sections' area. The size factor is computed, as previously described in Chapter 3 (Equation 3.9). Following the generic steps of the microeconomic analysis, the selected pavement sections for funding in each year were grouped into two their asset categories: Interurban, and Rural. The MU/$ values of the last selected road sections in each category were analyzed to determine whether the equality was maintained across them or not. Table 4.3, similarly to Tables 4.1 and 4.2, shows the analysis results for each rehabilitation year. At year 4, for example, the optimum number of assets allocated funds is 99 (33 interurban and 66 rural). The marginal utility per dollar (MU/$) associated with the last interurban and the last rural road sections selected are 0.021 and 0.022, respectively, which are very close. Similarly for the remaining years within the planning horizon, the values are very close in each year.

Table 4.3 Microeconomic analysis of optimal results for the pavement case study

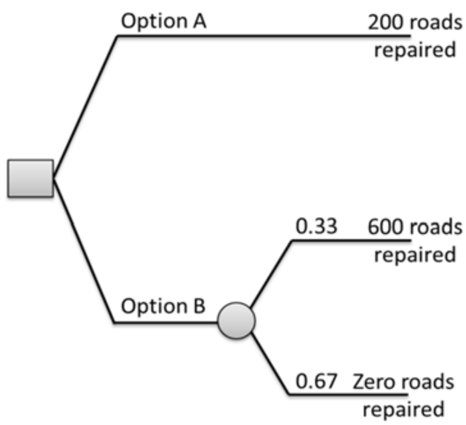
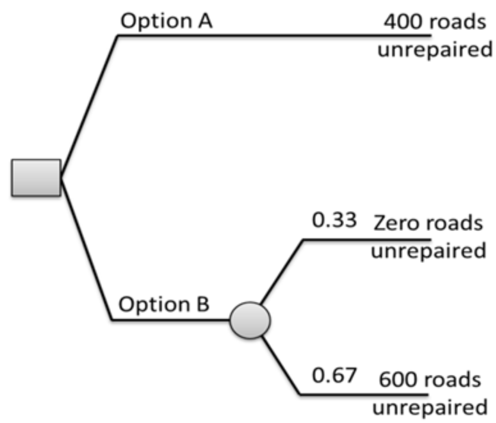
	Year 1		**Year 2**		**Year 3**		**Year 4**		**Year 5**	
	No.	**MU/$**	**No.**	**MU/$**	**No.**	**MU/$**	**No.**	**MU/$**	**No.**	**MU/$**
Urban roads	63	0.120	33	0.071	45	0.043	33	0.021	22	0.008
Rural roads	177	0.114	126	0.071	95	0.041	66	0.022	28	0.007
Total	240		159		140		99		50	

The microeconomic analysis in Tables 4.1, 4.2, and 4.3, thus, has showed that an approximate equality of the marginal utility per dollar has been maintained across the different asset categories, at alternate levels of analysis (e.g., system- or component-levels) in both case studies. Hence, it confirms the consistency of the optimal results with the law of equi-marginal utility per dollar of the consumer theory. Accordingly, from a microeconomics perspective, optimum fund-allocation can be defined as an equilibrium state in which balanced and equitable allocations are made so that the utility per dollar is equalized for all asset categories. This equilibrium state, therefore, can be used as a benchmark condition that must be achieved to economically justify fund-allocation decisions. Accordingly, the proposed microeconomic analysis can be readily used as a stand-alone benchmark test to examine the quality of any fund-allocation mechanism.

4.3 Examining Decision-making Behaviours in Infrastructure Funding

Most of the existing efforts related to finding optimum fund-allocation decisions for rehabilitation purposes, target maximizing the return (Gain or Utility) from the allocated money. It is important to emphasize that the optimization results, that were obtained in Chapter 3 and tested in the previous section, were also produced using the common strategy of maximizing gain. However, as previously discussed in Chapter 2 (Section 2.6.1), decisions can vary when framed with respect to loss rather than gain. Thus, in an effort to investigate the difference between the two strategies: maximizing gain and minimizing loss, this research models the concept of “Loss-aversion” in the infrastructure rehabilitation problem by framing the problem with respect to loss and compares it against the common approach of maximizing gain through extensive experiments.

Loss-aversion refers to people's tendency to strongly prefer avoiding loss than acquiring gain. To demonstrate how framing variations between the gain and loss perspectives of behavioural economics can apply to infrastructure rehabilitation, a hypothetical case of 600 roads that are in urgent need for repairs is considered to avoid user dissatisfaction and any potential for accidents [the example is modified from Tversky and Kahneman (1986) previously described in Chapter 2 , section 2.6.1, which discussed a problem in a different but analogus context]. The case has two options for funding repairs: A or B which are framed once in terms of gain, and once in terms of loss as shown in Figure 4.4. From a gain framing perspective, option A is to accept a guaranteed fund to repair 200 out of the 600 roads, while option B is to wait for another high-risk fund (33% approval chance) to fix all roads. From a loss framing perspective, on the other hand, option A is a guaranteed loss of leaving the majority of roads (400) unrepaired, while option B is risky but has some chance of leaving zero unrepaired roads. Figure 4.4 shows the relevance of the loss-aversion concept to the domain of infrastructure rehabilitation and the need to examine its impact on funding decisions.

Problem description in terms of GAIN	Problem description in terms of LOSS
Funding Option A: provides pre-approved funds to repair 200 roads only. Funding Option B: Larger fund to repair all the 600 roads, but has only 33% chance of approval.	Funding Option A: The small fund will certainly leave 400 roads unrepaired, thus creating large user dissatisfaction and large potential for accidents. Funding Option B: Risky fund but has good chance of repairing all roads, thus avoiding dissatisfaction and potential accidents.
	

Note: This figure is an illustration to show the application of the loss-aversion concept to the domain of infrastructure rehabilitation, and the need to examine its potential impact on fund-allocation decisions

Figure 4.4 Framing funding decisions from a gain and loss perspectives

To examine the influence of framing variations between gain-seeking and loss-aversion perspectives on infrastructure rehabilitation decisions, the network-level optimization model developed for the pavement case study (Chapter 3) has been modified to accommodate both gain and loss perspectives. Thus, two types of optimization models have been developed:

1. Loss-aversion model
2. Gain-maximization model

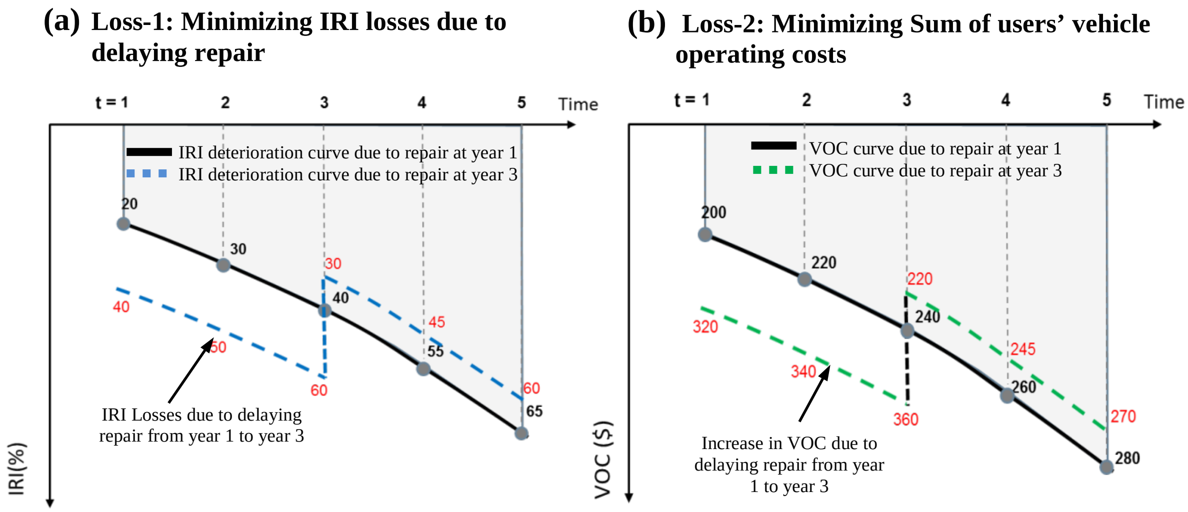
The objective function in the first type is set to minimizing loss, while second type is set to maximizing gain. The variables and constraints of both are as previously described in Chapter 3.

4.3.1 Loss-aversion Model

In this model formulation, the objective function is framed from a loss perspective and set to minimize the loss associated with any rehabilitation decision. Generally, loss can be represented in different ways (e.g., loss of opportunity to repair other assets, loss of asset's service life, etc.), however in this research, loss due to delayed repairs or no repairs has been represented in two alternate ways that suit the available case study information (Figure 4.5): (1) sum of IRI losses, and (2) sum of users' vehicle operating costs (VOC).

Figure 4.5 shows an example road section that is decided to be rehabilitated at year 3 (i.e., has lost the opportunity to be rehabilitated at year 1 and 2). Figure 4.5a shows two IRI deterioration curves, one in case of rehabilitation at year 1, while the other curve is in case of delayed rehabilitation to year 3. The lost opportunity due to rehabilitation decision is quantitatively calculated as the difference in the IRI values between the two deterioration curves, which gives a value of 40, as shown at the bottom of the figure. Summing the losses associated with all repair decisions provides the overall network loss.

As an alternative to this loss representation, Figure 4.5b shows the loss in terms of VOC which is calculated from the given case study data. In this case, the loss is quantitatively calculated as the sum of the resulting VOC values due to delaying the repair to year 3. Thus, the overall network loss is the sum of the VOCs associated with a given combination of rehabilitation decisions. In the second formulation, repair at year 1 is not taken as a reference to compute the loss as in the first formulation due to the fact that VOC in any case is an innate loss.



Disutility (DU_{i3}) = (40+50) – (20+30) = 40   Disutility (DU_{i3}) = (320+340+220+245+270) = 1395

Figure 4.5 Schematic of two disutility (Loss) formulations

In either formulation, the objective function is to minimize the network overall loss or disutility (DU_N). Mathematically, the objective function in both cases is as follows:

Minimize DU_N = weighted sum of assets' losses due to delayed or no repairs

$$= \frac{\sum_i [DU_{i0} \times (1 - X_{ij}) \times RIF_i]}{\sum_i RIF_i} + \frac{\sum_i [\sum_j (DU_{ij} \times X_{ij}) \times RIF_i]}{\sum_i RIF_i} \quad (4.4)$$

Where DU_{i0} is the disutility associated with asset *i* in case of no repair, while DU_{ij} is the disutility associated with asset *i* in case of repair at any year *j* (due to delayed repairs), calculated as follows:

Case I: Minimize IRI losses (Named Loss-1 model)

$$DU_{ij} = [\sum_t IRI_{ij}^{t} - \sum_t IRI_{i1}^{t}] \times SF_i, \text{ If } IRI_{ij}^t > IRI_{i1}^t, \text{ otherwise } DU_{ij} = 0 \quad (4.6)$$

$$DU_{i0} = [\sum_t IRI_{i0}^{t} - \sum_t IRI_{i1}^{t}] \times SF_i, \text{ If } IRI_{i0}^t > IRI_{i1}^t, \text{ otherwise } DU_{i0} = 0 \quad (4.7)$$

Case II: Minimize VOC (Loss-2 model)

$$DU_{ij} = \sum_t VOC_{ij}^{t} \tag{4.8}$$

$$DU_{i0} = \sum_t VOC_{i0}^{t} \tag{4.9}$$

In case I, DU_{i0} is the difference between the best IRI values in case of repair at year 1 and the IRI values in case of no repair, while DU_{ij} is the difference between the best IRI values in case of repair at year 1 and the IRI values in case of repair at any year *j* within the planning horizon. SF_i is a Size Factor to take into consideration the differences in the road sections' areas (Equation 3.9). On the other hand for case II, DU_{i0} is the sum of the resulting VOC values due to no repair, while DU_{ij} is the sum of the resulting VOC values due to repair at any year *j* within the planning horizon. IRI_{ij}^{t} is the IRI values of asset *i* at any time t in the planning horizon due to repair at any decision year *j*, IRI_{i1}^{t} is the IRI values of asset *i* at any time t in the planning horizon due to repair at decision year *j* =1, and IRI_{i0}^{t} is the IRI values of asset i at any time t in case of no repair. Similarly is for VOC parameters. RIF_i is the relative importance factor (0–100) of each asset *i*, which is used to capture the decision maker's preferences towards the importance of the different asset categories (e.g., interurban versus rural) and accordingly represent the improvement effects on the same scale.

Using the above equations on the example illustrated in Figure 4.5: $X_{ij} = 1$, since the asset will be repaired at year 3 eventually. For case I, $DU_{ij} = (IRI_{i3}^{1} + IRI_{i3}^{2}) - (IRI_{i1}^{1} + IRI_{i1}^{2})$ = (40+50) – (20+30) = 40. For case II, $DU_{ij} = (VOC_{i3}^{1} + VOC_{i3}^{2} + VOC_{i3}^{3} + VOC_{i3}^{4} + VOC_{i3}^{5}) =$ (320+340+220+245+270) = 1395.

4.3.2 Gain-maximization Model

In this model (named Gain-1 model), the objective function is framed from a gain perspective and set to maximize the utility (gain) associated with any rehabilitation decision. The utilities were defined in terms of the improvement in the IRI values due to rehabilitation at a given year compared to no-rehabilitation decision (Figure 4.6). The figure shows an example road section that is decided to be rehabilitated at year 3 (i.e., has gained the opportunity to be rehabilitated at year 3 in comparison to no repair). The figure shows two IRI deterioration curves, one in case of repair at year 3, while the other curve is in case of no repair. The shaded area represents the opportunity gained due to the rehabilitation decision, with the utility quantitatively calculated as the difference in IRI values between the two deterioration curves giving a value of 75 as shown on the figure. Summing the utilities associated with asset rehabilitation decisions provides an overall network gain (U_N) and the objective function is set to maximize the network overall gain, which is represented mathematically as follows:

Maximize U_N = Weighted sum of assets' utilities due to repair

$$= \frac{\sum_i [\sum_j (U_{ij} \times X_{ij}) \times RIF_i]}{\sum_i RIF_i} \tag{4.9}$$

Where, $$U_{ij} = [\sum_t IRI_{ij}^{t} - \sum_t IRI_{i0}^{t}] \times SF_i \tag{4.10}$$

Where U_{ij} is the utility associated with asset i in case of repair at any given year j within the planning horizon. In case of no repair, U_{ij} = 0. Similarly to the Loss models, SF_i is a Size Factor to take into consideration the differences in the road sections' areas (Equation 3.9).

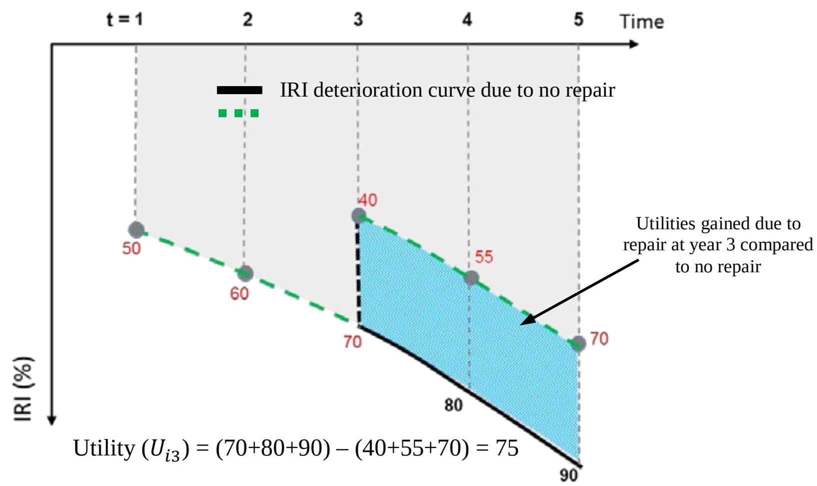


Figure 4.6 Schematic of utility (Gain) formulation

CPLEX Solver, in GAMS modelling environment, has been used to implement the above three optimization models. The GAMS/CPLEX optimizations results for the case study are discussed in the next section.

4.3.3 Optimization Experiments and Comparison of Results

Three different models are developed in GAMS to implement the two Loss-averse formulations (Loss-1, Loss-2, models) and one Gain-based formulations (Gain-1 model). The screen capture in Figure 4.7 shows a sample portion of GAMS model for utility maximization. The bottom part of the figure shows a sample portion of the optimization results that were exported to the Excel sheet to facilitate further analysis. After implementing GAMS optimization models for both the Loss and Gain formulations, the optimum rehabilitation year for each road section in each experiment was determined. The overall network condition, in terms of the average IRI values of all assets among all years, has improved to 1.45 compared to the original condition of 1.7 (without any repair), under an annual budget limit of $8 Million.

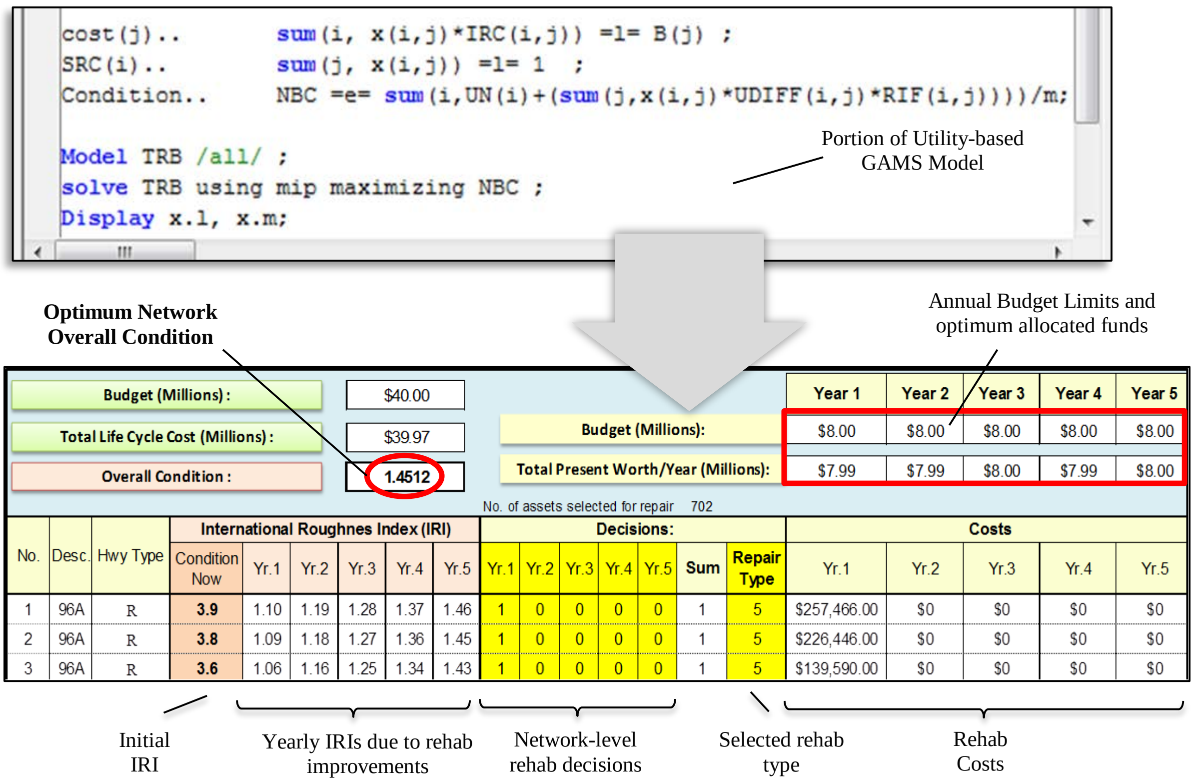


Figure 4.7 Network-level utility-based optimization results for case study

An extensive comparison of the results of all experiments is shown in Table 4.4, which has been created based on a detailed anatomy of the optimization results, in an effort to understand how the decision strategy relates to road size, road initial condition, and traffic volume. Based on Table 4.4, the following observations could be made:

- All three experiments provided good solutions that represent different mechanisms for allocating infrastructure funds, thus giving the decision maker credible options to choose from;
- Gain-1 model provided the best overall network condition with Loss-1 model being second best;
- Loss-2 model achieved the highest improvement with respect to the vehicle operating costs (VOC);

Table 4.4 Analysis of the optimization results of Loss vs. Gain model

Row	Point of Comparison	Gain-1	Loss-1	Loss-2
1	**Objective Function**	**Max. IRI Utility**	**Min. IRI Disutility**	**Min. VOC Disutility**
2	Overall Condition (IRI)	1.45	1.46	1.59
3	No. of roads selected for rehab.	655	621	281
4	Total Area Repaired (m^2)	6,464,643	6,322,751	5,717,646
5	Total Length Repaired (m)	545,550	539,330	467,640
6	Total reduction in VOCs ($)	6,958,019	7,180,097	13,796,104
Road Section Size (Large to Small):				
7	No. of roads with area >40000 m^2 **Large**	8	10	39
8	No. of roads with area within 25000 and 40000 m^2	23	27	27
9	No. of roads with area within 20000 and 25000 m^2	22	22	21
10	No. of roads with area within 15000 and 20000 m^2	61	55	14
11	No. of roads with area within 10000 and 15000 m^2	109	95	26
12	No. of roads with area within 5000 and 10000 m^2	252	235	55
13	No. of roads with area within 2000 and 5000 m^2	171	168	90
14	No. of roads with area < 2000 m^2 **Small**	9	9	9
Road Section Initial Condition (Bad to Good):				
15	No. of roads with Initial IRI (IRI_0) >=3.5 **Bad**	7	7	2
16	No. of roads with IRI_0 >=3.0 and <3.5	14	15	6
17	No. of roads with IRI_0 >=2.5 and <3.0	58	59	22
18	No. of roads with IRI_0 >=2.0 and <2.5	112	114	78
19	No. of roads with IRI_0 >=1.5 and <2.0	205	206	112
20	No. of roads with IRI_0 >=1.0 and <1.5	194	174	47
21	No. of roads with IRI_0 >=0 and <1.0 **Good**	65	46	14
Road Section Traffic Volume (High to Low):				
22	No. of roads with AADT >=40000 **High**	1	1	4
23	No. of roads with AADT >=30000 and <40000	8	7	13
24	No. of roads with AADT >=20000 and <30000	50	46	75
25	No. of roads with AADT >=10000 and <20000	84	82	75
26	No. of roads with AADT >=5000 and <10000	167	163	77
27	No. of roads with AADT >=2000 and <5000	283	267	34
28	No. of roads with AADT >=1000 and <2000	53	49	3
29	No. of roads with AADT <1000 **Low**	9	6	0

- Comparing the different models, funds are allocated heuristically as follows:
  - Gain-1: allocates more funds to small-size road sections (row11), moderately-deteriorated roads (rows 18 & 19), and roads exposed to low-traffic (row 26);
  - Loss-1: allocates more funds to small-size road sections (row11), moderately-deteriorated roads (rows 18 & 19), and roads exposed to low-traffic (row 26); and
  - Loss-2: same strategy as Loss-1, yet allocates more funds to v. large sections (row 6) exposed to medium-traffic (rows 23,24 & 25); and
- To further examine the difference between gain and loss experiments, the seemingly similar results of Gain-1and Loss-1 experiments are further analysed, as shown in Figure 4.8. Looking at the year by year funding pattern, it can be noticed that Gain-1 starts by allocating funds in year 1 to roads with worse initial condition than the Loss-1 model. Thus, Gain-1 ends up fixing less number of these roads in year 1. Along the remaining years in the planning horizon, Gain-1 allocates funds to roads with better conditions than the Loss-1 model. It seems that the Loss-based model starts by funding relatively better roads to avoid greater loss in performance, which is consistent with its funding strategy;
- Despite providing the highest mathematically calculated gain, the Gain-1 model can only be useful if its strategy makes sense to decision makers;
- Loss-2 experiment, ended up consuming budget on much fewer roads due to its strategy of allocating more funds to large-size and medium-traffic road sections; and
- Loss-2 experiment spends more money on interurban roads (approximately 65%), while the other experiments spend more money on the rural roads (approximately 74%).

Comparing the results of the Gain-1 and Loss-1 experiments, it can be concluded that their strategies of allocating the funds are generally comparable (despite the differences discussed in

Figure 4.8). This is because the two experiments are representing either gain or loss with respect to the assets' condition. Perhaps the most interesting result, is the one obtained from the Loss-2 experiment which minimizes the users' vehicle operating costs associated with the different rehabilitation decisions. The representation of loss in this experiment is different and focuses on a social aspect for the users rather than targeting the loss in the asset condition from the authorities' perspective, as in the Loss-1 experiment. It has resulted in a very different strategy to allocate the funds and has achieved the highest improvement in the vehicle operating costs incurred by users. This research, thus, shows that framing the problem to consider the loss-aversion perspective, and considering different stakeholders' preferences can lead to a different infrastructure fund-allocation strategy, and hence different economic analysis.

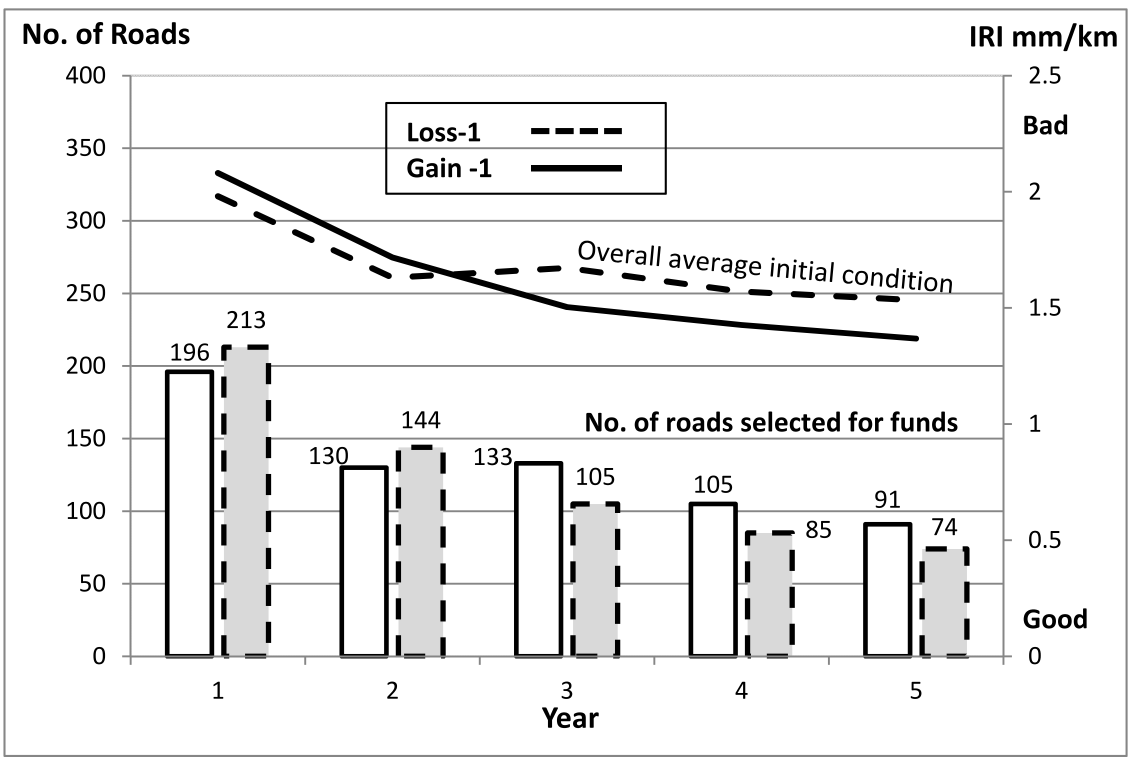


Figure 4.8 Analysis of Gain-1 vs. Loss-1 model results

4.4 Conclusion

Using well-established microeconomic concepts, the spending behaviour of a consumer who spends a limited income on various needs has been mapped to that of a government agency that has a limited budget from the tax payers' money to rehabilitate many infrastructure assets. The analysis of the optimum fund-allocation results in the two real case studies of pavements and buildings has proved that microeconomic concepts are applicable to the infrastructure fund-allocation problem. Such concepts provide decision makers with an economic benchmark tool to test the solution quality obtained from any fund-allocation mechanism, and justify decisions.

Considering the loss-aversion concept into the decision-making process by targeting minimizing the users' loss, as an objective function, leads to a different fund-allocation strategy than the traditional approach of maximizing the performance gain. Incorporating behavioural aspects into asset management decisions, therefore, can better reflect the preferences of all stakeholders into the decision making process. In essence, infrastructure funding is an important economic decision and integrating the two worlds of Microeconomics and infrastructure asset management help provide an economic justification for spending tax payer's money on infrastructure rehabilitation projects.

Chapter 5

Enhanced Benefit-Cost Analysis (EBCA) and Visualization

5.1 Introduction

This chapter describes a new microeconomic-based decision support framework that incorporates two main components: (1) An enhanced benefit-cost analysis (EBCA) heuristic approach; and (2) A visual sensitivity analysis tool. It explains step-by-step the development of the proposed heuristic approach, and its implementation both manually and using a simple optimization algorithm. The school buildings real case study has been used to demonstrate the framework's features, validate its applicability, and affirm the quality of solution by comparing the results against the existing fund-allocation methods in the literature.

5.2 Microeconomic-based Framework

The proposed microeconomic-based framework for infrastructure funding adopts the two consumer theory principles, discussed earlier in Chapter 2. The framework has two components (Figure 5.1): (1) A heuristic procedure that can arrive at optimum choices at different levels utilizing the law of equi-marginal utility per dollar; and (2) A visual what-if analysis tool to study the sensitivity of decisions, inspired by the concept of indifference curves. The proposed framework is generic and can be applied at any decision level, as shown in the right side of Figure 5.1. It can be applied at the strategic (government) budgeting level of decisions, where a budget needs to be divided among competing departments, or at the operating level where limited funds need to be allocated to numerous competing assets (Whether at the system-level or the more detailed component-level of decisions). This research, however, focuses on the infrastructure fund-allocation decision level. To demonstrate the features of the two framework components, the real case study related to school buildings (Toronto District School Board, TDSB, previously described in Chapter 3) has been used. The results are later compared to those obtained using existing methods in the literature, as discussed in the next section.

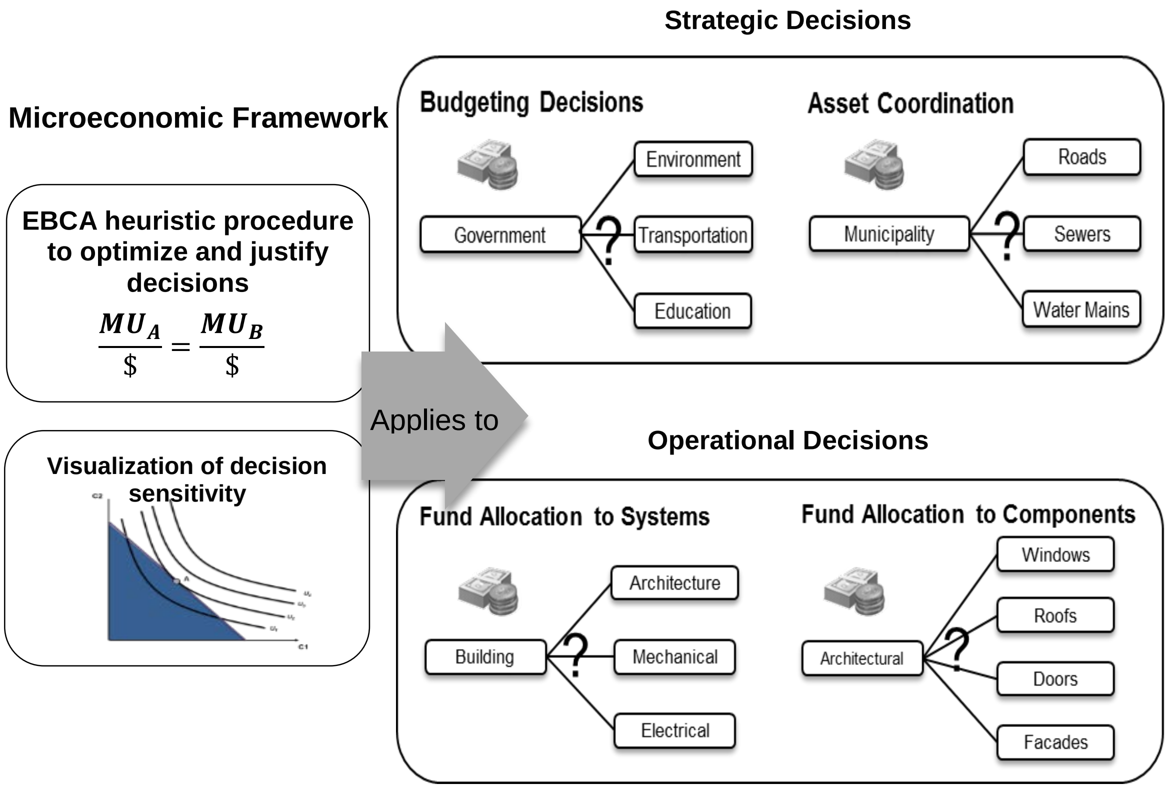


Figure 5.1 Components of the proposed microeconomic framework

5.3 Microeconomic-based EBCA Heuristic Approach

To optimize fund-allocation decisions in consistency with the microeconomic origins of benefit-cost analysis that Dupuit initiated, and to handle the multi-level complexity of the infrastructure fund-allocation problem, the proposed enhanced benefit-cost analysis (EBCA) heuristic approach capitalizes on the well-established consumer theory. To consider both project- and network-level decisions, the proposed approach is built upon the Multiple Optimization and Segmentation

Technique (MOST) of Hegazy and Elhakeem (2011). To reduce problem size in the MOST technique, as previously described in Chapter 3, project-level analysis is done first one year at a time to determine for each asset the best rehabilitation scenario (e.g., minor, major, or full replacement) that maximizes the benefit-cost ratio assuming the rehabilitation year will be in year 1, year 2, etc. This analysis provides a pool of best potential repair strategies, and associated costs, that is used as a lookup input table to simplify the network-level analysis. At the network-level also, the segmentation technique segments the problem into yearly smaller-size optimizations to decide on the assets' best renewal timings (facilitated only by the pre-analysis at the project level), using Genetic Algorithms (GA) optimization to handle this large-scale problem.

Despite the capability of MOST to reasonably handle large-scale problems, the number of variables for each yearly optimization at the network-level is 800, which produces a large solution space that makes the problem complex and time-consuming. In addition, due to the random combinatorial nature of the GA optimization model, the results are lacking a transparent justification and explanation behind the decisions (i.e., no strategy behind the decisions). In this research, the heuristic approach follows the same yearly segmentation process (i.e., considering one year at a time) at the network-level; however, it replaces the complex network-level optimization with a heuristic method inspired by the microeconomic law of equal marginal utility per dollar of the consumer theory (as illustrated in Figure 5.2). While for the project-level, the proposed approach is building upon the project-level analysis, using benefit-cost ratio, of Hegazy and ElHakeem (2011). In the microeconomic literature, the concept of equal marginal utility per dollar has been proven to arrive at optimum allocation of a limited fund by targeting equilibrium (equality) among the marginal utility per dollar spent on the different consumption categories, rather than the typical approach of maximizing benefits or minimizing costs. As such, optimum fund-allocation is represented by an equilibrium state at which the following relationship holds:

$$(\frac{MU}{\$})_{xth} = (\frac{MU}{\$})_{yth} \tag{5.1}$$

Where, x^{th} and y^{th} are the last assets to be selected from each category.

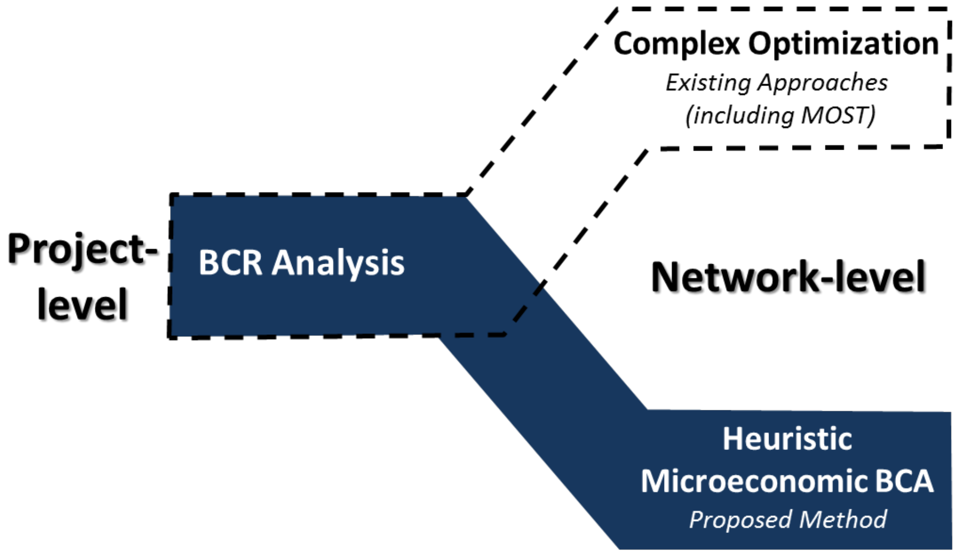


Figure 5.2 Proposed methodology to enhance infrastructure fund-allocation

To adopt the law of equal marginal utility per dollar of consumer theory; the basic premise of this research is the analogy between a consumer who has a limited income to spend on various expenditure categories, and a public agency with a limited yearly budget to allocate to various renewal (rehabilitation) expenditures. In the infrastructure case, the benefit that results from a given rehabilitation activity for an asset *i* is the marginal utility that the network of assets gain. In this research, the benefits (utility) are defined in terms of the assets' condition improvement after renewal (can be extended to multiple criteria in future research). Using the law of equi-marginal utility per dollar in Equation (5.1), the proposed heuristic approach to arrive at optimum fund-allocation decisions is developed as shown in Figure 5.3. The approach is a network-level process of 5 steps that is applied one year (*j*) at a time, thus, it facilitates mapping the consumer case in each year in the planning horizon, to arrive at the optimum decision that maintains an equilibrium state among the different asset categories.

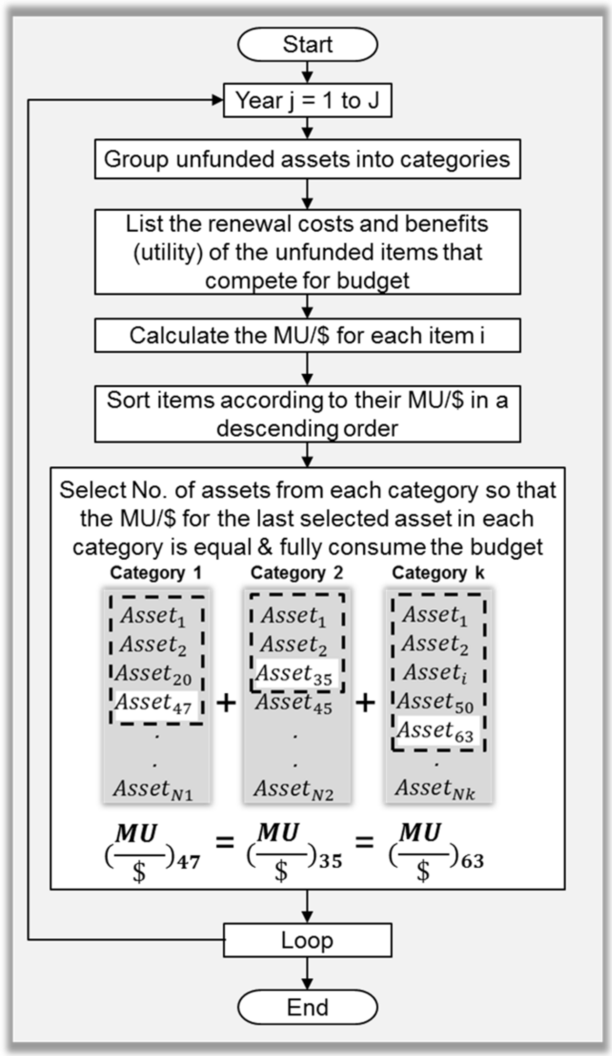


Figure 5.3 Proposed microeconomic EBCA approach for Network-level analysis

5.3.1 Heuristic Procedure Steps

To demonstrate the heuristic procedure steps of Figure 5.3, the building case study (Chapter 3) is used. Following the heuristic process of equalizing the marginal utility per dollar among all categories (Figure 5.3), the process is applied to the case study as follows:

For each year in the planning horizon:

1. Group unfunded assets into their categories (Architectural, Mechanical, and Electrical);
2. List the performance improvement and the renewal cost for each asset based on the LCCA calculations (Chapter 3), assuming all assets will be funded this year;
3. Compute the Marginal utility per dollar (MU/$) for each asset by dividing the performance improvement by the renewal cost;
4. Sort the assets in a descending order, according to the MU/$; and
5. Select assets for funding starting from the top of the sorted list in each category till the MU/$ value of the last selected asset in each category is almost equal, and the budget for this year is fully exhausted. Move unfunded assets beyond this equilibrium point to the next year in the planning horizon.

Proceed to step 1 for the analysis of the next year, until last year in the planning horizon.

Figure 5.4 shows the application of the heuristic process steps to the case study data in year 1. The assets are grouped according to their system-level categories (Architectural, Mechanical, and Electrical), and sorted in a descending order according to their marginal utility per dollar values. The “Cum. Cost” column represents the total cumulative rehabilitation costs that correspond to a total number of allocated assets in each category. The shaded part shows the optimum (equilibrium) combination of assets for year 1, which is 124 architectural, 51 mechanical, and 43 electrical assets. The total cost associated with this combination is $9,994,640 ($4,509,670 + $3,415,870 +

$2,069,100), which almost fully exhausts the available budget while maintaining an equilibrium state among the asset categories.

Architectural Assets		
No.	MU/$	Cum. Cost
1	2.6726	$1,815
2	2.6207	$3,630
3	2.2804	$5,445
:	:	:
:	:	:
:	:	:
:	:	:
:	:	:
124	**0.0452**	**$4,509,670**
125	0.0450	$4,558,070
126	0.0447	$4,606,470

Mechanical Assets		
No.	MU/$	Cum. Cost
1	0.2516	$6,050
2	0.2309	$18,150
3	0.2040	$36,300
:	:	:
:	:	:
:	:	:
:	:	:
46	0.0439	$2,968,170
47	0.0438	$3,064,970
48	0.0436	$3,161,770
49	0.0435	$3,234,370
50	0.0435	$3,325,120
51	**0.0434**	**$3,415,870**

Electrical Assets		
No.	MU/$	Cum. Cost
1	0.2445	$24,200
2	0.2312	$48,400
3	0.1996	$66,550
:	:	:
:	:	:
42	0.0482	$1,960,200
43	**0.0431**	**$2,069,100**
44	0.0409	$2,165,900
45	0.0398	$2,238,500

Figure 5.4 Sample of selected assets in Year 1 using EBCA approach

A summary of the heuristic approach results for all years is provided in Table 5.1, showing the number of assets selected from each category; the MU/$ of the last selected asset in each category; the total cost associating the selected assets in each category; and the total annual rehabilitation costs. It can be noted from the table that the equilibrium is maintained across the MU/$ values for the last selected asset in each category for all years in the planning horizon, while almost fully exhausting the $10M budget.

It has been noted that because this solution was achieved manually, it is possible to try minor changes to see if a better solution can be achieved. This trial and error process, however, can be inaccurate when a large number of categories exist.

Table 5.1 Summary results of the selected assets, using EBCA heuristic approach

	Architectural			Mechanical			Electrical			Total Cost($)
	No.	MU/$	Cost($)	No.	MU/$	Cost($)	No.	MU/$	Cost($)	
Yr1	124	**0.0452**	4,509,670	51	**0.0434**	3,415,870	43	**0.0431**	2,069,100	9,994,640
Yr2	47	0.0257	4,222,130	56	0.0257	5,286,490	6	0.0258	490,050	9,998,670
Yr3	51	0.0142	5,962,760	34	0.0145	4,005,100	0	-	-	9,967,860
Yr4	39	0.0076	6,310,600	22	0.0078	3,684,450	0	-	-	9,995,050
Yr5	34	0.0031	6,649,958	17	0.0033	3,339,600	0	-	-	9,989,558
Overall Network Deterioration Index = 31.79436 (improvement from 54.1 without Rehab.)										

5.3.2 Simplified Optimization Process

To facilitate finding the optimum solution without trial and error, a small optimization model was developed and solved using the Evolutionary algorithm of Excel Solver (Figure 5.5). The model has three integer variables (three asset categories), in addition to two constraints: the variable value (number of selected assets in a category) is less than or equal the total available; and the total costs of all selected assets exhausts the available budget. To satisfy the equilibrium condition, the objective function is set to minimize the variance across the MU/$ values of the last selected asset from each category. To make sure that the MU/$ values are equal, a ratio (called Equality Factor) between the sides of Equation (5.1) is set to 1.0 as a third constraint, as follows:

$$\text{Equality Factor } (EF_{i,i+1}) = \frac{MU/\$_{category\ i+1}}{MU/\$_{category\ i}} \qquad (5.2)$$

Thus, if the number of categories is N, then the number of equality factors is N-1. Mathematically, the formulations of the variables, objective function, and constraints are represented by equations 5.3 to 5.7. Such an optimization has a small solution space, as it does not depend on the number of assets, thus it is applicable to very large-scale problems that are hindered by other existing representations.

Variables: N variables, each representing the number of assets (X_i) selected from each sorted category *i*;

X_i, X_{i+1}, …………….X_N (5.3)

Objective Function: minimize variance among the MU/$ values of the last selected asset in the number of assets X_i selected from each category *i*

Minimize Variance ($MU/\$_{X_i,category\ i}$, $MU/\$_{X_{i+1},category\ i+1}$,….., $MU/\$_{X_N,category\ N}$)(5.4)

Constraints:

$\sum Costs \ \leq Budget$ (5.5)

$0.95 \leq EF_{i,i+1} \leq 1.05$, where *i* = 1, 2,….., *N*-1 (5.6)

$X_i \ \leq \ K_i$, where *K* is the number of assets available in category (*i*) (5.7)

Figure 5.5 shows the application of the previous formulations to the building case study, using solver. Since there are three asset categories, the number of variables is three, and the number of the needed equality factors is two. In the figure, year 1 results are demonstrated, where the optimum combination arrived at, is to repair 124 Architectural, 51 Mechanical, and 43 Electrical assets, with the budget being almost fully exhausted, and the MU/$ values are very close to each other. This optimum combination is identical to the manual solution but without trial and errors.

To validate the quality of the results obtained using the proposed heursitc approach, the results were compared, as shown in Table 5.2, to the Genetic Algorithms results of Hegazy and ElHakeem (2011), and to the global optimum solution of the mathematical model developed by Rashedi (2011) using CPLEX solver in (GAMS) modelling environment (Chapter 3). Table 5.2 shows the overall network deterioration without any rehabilitation; using the three models; and using also the typical simple ranking approach of selecting the worst assets first.

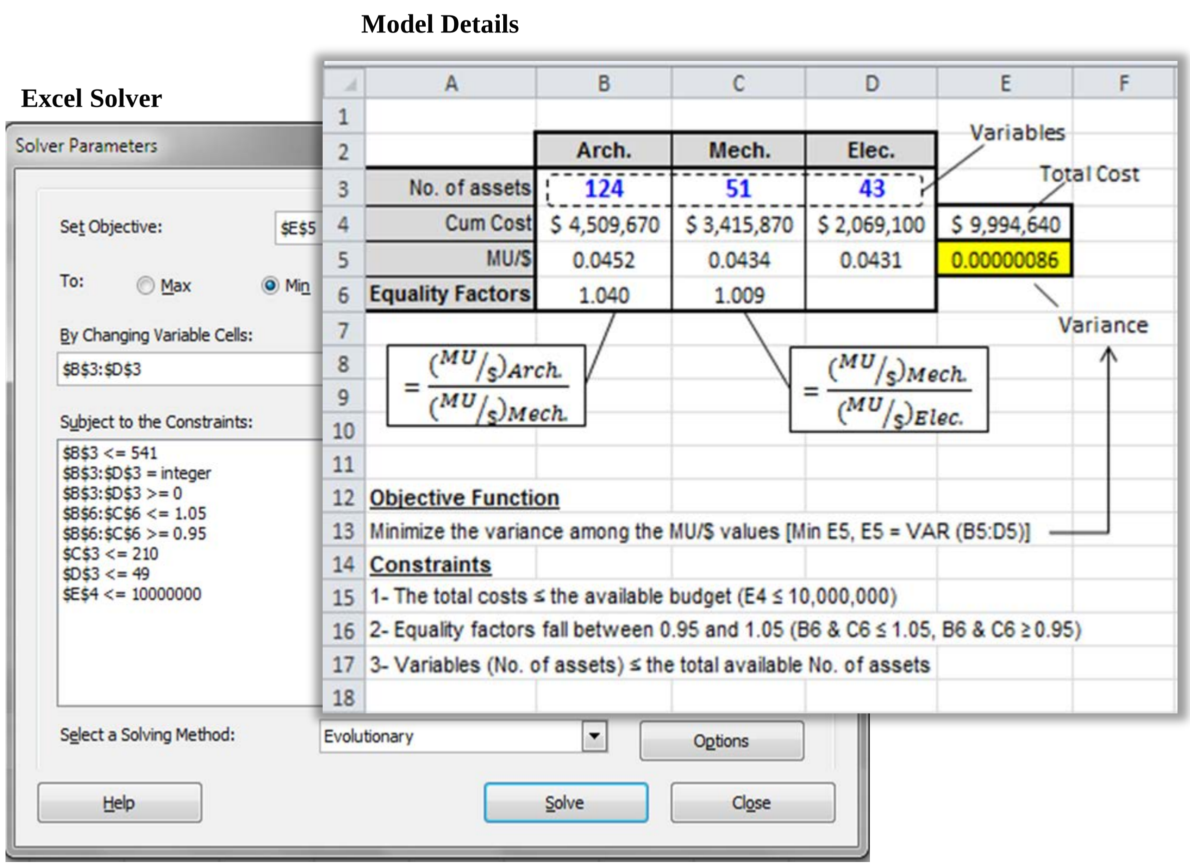


Figure 5.5 Optimization Setup for Year 1

Table 5.2 Comparison among solution approaches

	Overall Network Deterioration
Without Rehabilitation	54.15
Approach:	
Simple Ranking	44.890
GA Optimization	33.181
Mathematical Optimization (GAMS/CPLEX)	31.710
Heuristic Approach	31.794

It can be noted from the Table 5.2 that the heursitic approach outperforms the simple ranking and GA approaches, and is comparable to the global optimum solution using mathematical optimization. The proposed heuristic procedure, however, as opposed to the black box solution obtained by GAMS and the difficulty to explain the results, provides optimum decision supported with transparent economic justification and a structured strategy behind the decisions made. To demonstrate the additional benefits of the optimized heuristic approach, as compared to the mathematical optimization, a comparison using the case study data is carried out between the two models with respect to the number of variables; solution space; etc, as shown in Table 5.3. The comparison clearly shows that the proposed simplified optimization method dramatically reduces the solution space while having much less complexity, and thus is more suitable for large-scale problems, and for extending this research to the case of mixed (co-located/corridor) assets, which can be very huge in size. Next Chapter dicusses the implementation of the proposed heuristic optimized method on a mixed assets case study.

Table 5.3 Proposed optimization model vs. existing optimization methods

	Proposed Optimization Model	**Mathematical optimization Models**
No. of variables	3 (categories)	800 (assets)
Solution space	541 x 210 x 49 (5,566,890)	2^{800} (6.668E+240)
Level of complexity	Low	High (need specfic coding)

5.4 Visualization of Fund-Allocation Decisions

The second important aspect of the proposed microeconomic framework is a new approach that visualizes fund-allocation decisions along with their associated utilities and costs. This visualization extends the “Indifference Curves” concept discussed earlier in Chapter 2 (which only visualized the total utility associated with any decision) by visualizing also the associated total costs with any decision or combination of assets, as shown in Figure 5.6.

The top part of the figure shows a 2-dimensional contour map (alternative representation of the indifference curves) of all possible decisions produced for the case study data of year 4 in the planning horizon using the EBCA approach, which has only two categories of components (architectural and mechanical), as shown in Table 5.1. The contour map shows color-coded regions that represent the total utility levels (network condition improvement) associated with the different combinations of architectural and mechanical components. The utility levels are computed from scaling the total utility (Currently, total utility is the total condition improvement; however, it can be extended, as part of future work, to integrate different types of performance indicators) associated with each combination of assets on a scale range from 1 to 10, where a level of 10 represents the highest total utility. The horizontal x-axis represents the number of architectural assets, and the vertical y-axis represents the number of mechanical assets. The bottom part of the figure, on the other hand, shows a set of curves that shows the total cost associated with different combinations of architectural and mechanical components. Similarly to the top part, the x-axis represents the number of architectural assets. Each curve represents a different number of mechanical assets, and the y-axis represents the total cost associated with each combination of assets. For example, point “a” on the plot represents the optimum combination, in year 4, of 39 architectural assets and 22 mechanical assets (Table 5.1), with a total utility level of 2, as shown in the top chart.

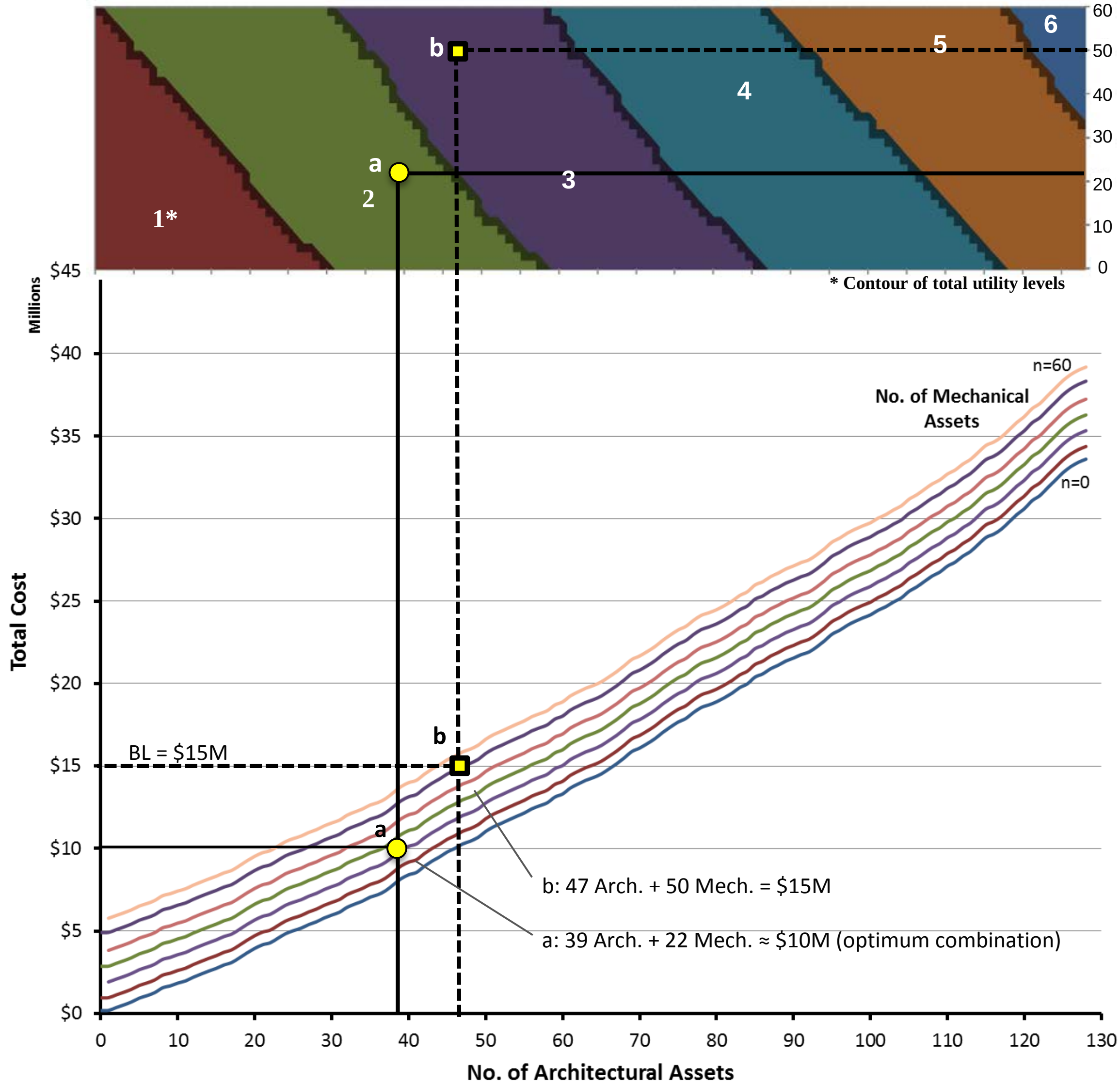


Figure 5.6 Visual what-if analysis chart for the results of year 4

The curves in Figure 5.6 also readily facilitate sensitivity analysis. The decision maker, for example, can investigate changes (such as increasing the budget limit and/or change the number of assets selected from each category, etc.) needed in order to move the optimum decision (point a) to a higher utility level. The curves can be used as well to determine the impact of different budget levels on decisions. For example, if the budget level is set to \$15M, then a feasible solution is to repair 47 architectural assets and 50 mechanical assets, which results in a higher total utility level of 3, as shown for point “b” on the plot. These charts can also easily facilitate decision-making among choices (combinations of assets) that have same total cost, but yield different levels of utility, and vice versa.

5.4.1 Potential Extension of the Visual Analysis Tool to Multiple Dimensions

The original indifference curves in the context of Microeconomics is a simple 2-dimensional contour map, as previously shown in Chapter 2 (Figure 2.5), where each curve represents the total utility that associate the different combinations of any two products. In this research, however, it was extended by the bottom chart in Figure 5.6 to represent as well the total cost that associates different combinations of any two assets. In an effort to visually represent both total utility and total cost that associate multiple assets (more than two), different multi-dimensional softwares were investigated (e.g., grapher, etc.). It has been found, however, that such tools are quite complex and sophisticated, especially in the field of infrastructure asset management where policy-makers request simple practical methods to make decisions. Therefore, to facilitate studying visually the sensitivity of funding decisions across multiple categories, a proposed approach is to produce 2D charts for any two categories while having the remaining categories fixed. For example, in the building case study, there are three asset categories, and Figure 5.6 represented year 4 decisions where only two asset categories are competing for funding. Thus, to represent the remaining years in the planning horizon where the three asset categories are competing for funding, multiple charts are produced for subsequent number of electric assets, such that each chart represents the total utility and cost associated with different combinations of architectural and mechanical assets, and number of electric assets that the chart was produced for, as shown in Figure 5.7.

Table 5.4 shows the preparation of data to be used to develop the multi-dimensional visual charts. The first column represents the category of assets which is kept fixed in the various combinations produced with the rest of the categories. These charts can end up being a set of charts that can facilitate studying the sensitivity of decisions in any rehabilitation project.

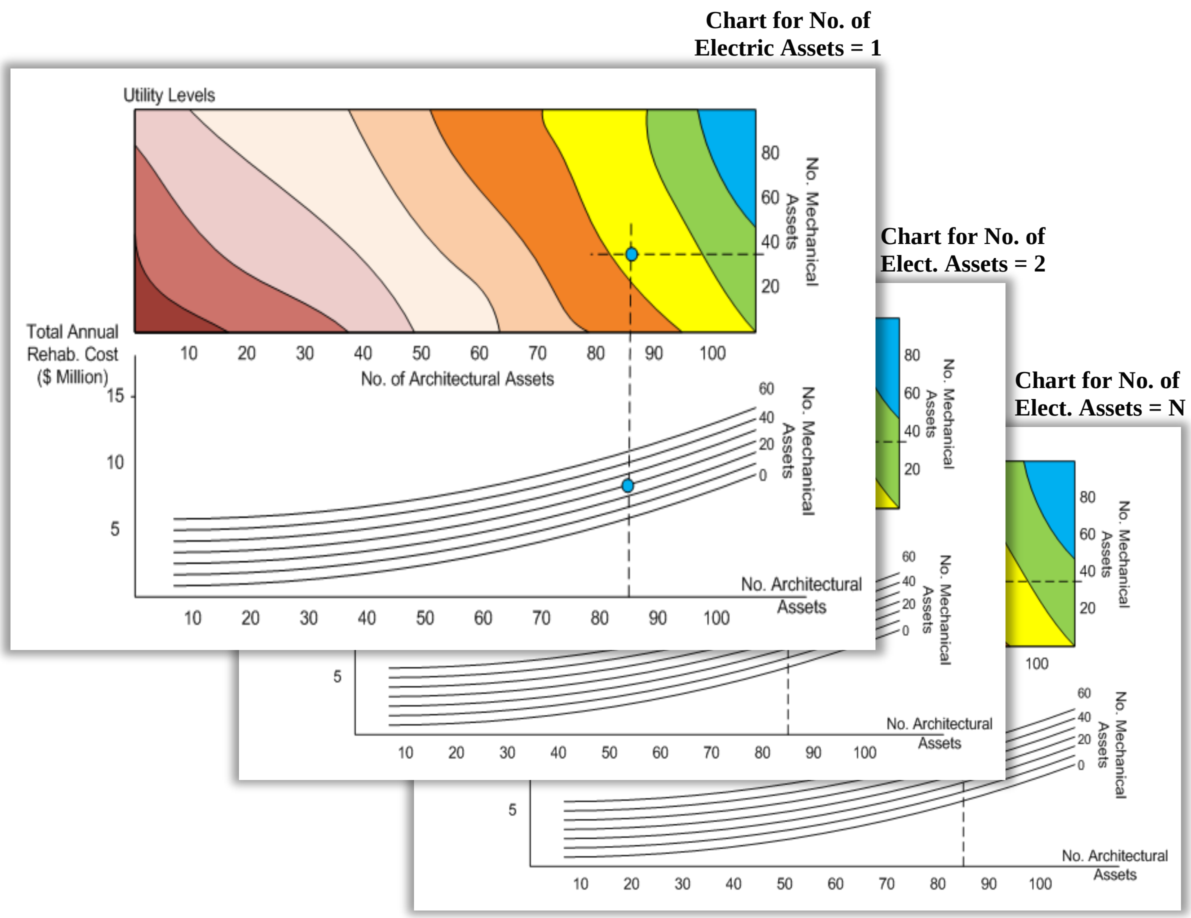


Figure 5.7 Multi-dimensional visual What-if analysis charts

In essence, Figures 5.6 and 5.7 provide new powerful graphical tools that can visualize all possible decisions with total utility and total cost associated with each decision, and study the sensitivity of decisions under any imposed changes through a simple What-If analysis.

Table 5.4 A Sample of data associated with a 3D indifference chart

No. of Electrical Assets	No. of Architectural Assets	No. of Mechanical Assets	Utility Level	Total Cost($)
1	1	1	10	25
		2	20	50
	:	:	:	:
	2	1	20	53
		2	25	63
	:	:	:	:
	3	1	25	70
		2	30	80

5.5 Conclusion

The proposed EBCA approach enhanced the benefit-cost analysis by targeting equilibrium (equality) among the different expenditure categories using the law of equal marginal utility per dollar of the consumer theory. The case study application has shown that targeting equilibrium and balanced fund-allocations can be a more practical and justifiable approach, rather than the typical approach of utility maximization. Moreover, the proposed heuristic approach has the benefit of being suitable to be applied manually or using a simple optimization model that dramatically reduces the solution space in comparison to the existing optimization models, and thus is more suitable for large-scale problems. The new visual sensitivity analysis tool also presents a powerful graphical and a What-If analysis tool that can visualize all possible decisions along with their associated utility and costs, and can readily facilitate decisions in case of tied situations and in case of any imposed changes in budget levels.

Chapter 6

Application of the EBCA Approach to Mixed Assets

6.1 Introduction

This chapter describes the application of the EBCA heuristic approach on a mixed assets case study where multiple assets are co-located and compete for funding using two alternative strategies for considering the coordination of rehabilitation work. The case study is a network of pavements and structures (bridges and culverts) that are located within the right of way. This chapter, also, describes earlier efforts that addressed this case study and the utilized approaches.

6.2 Mixed Assets Case study: The Challenge

This case study is a highway network of mixed assets that consists of a network of pavements along with the structures within the right of way including bridges, culverts, and signs. The case study was part of an asset management challenge posted at the 7th International Conference on Managing Pavements (Haas, 2008). The challenge was initiated with a worldwide call for Expressions of Interest, and aimed to determine a methodology to be used in practice by the road network investment decision makers to preserve the existing service level for the entire network, as shown in Appendix II. It was recommended that the respondents should achieve a strategic balance between investments on the interurban part of the network that has high traffic volumes and the investment on the rural part that has low traffic volumes (Haas, 2008).

In general the highway network consists of a pavement (road) network of 1293 road sections of two types: interurban and rural (350 and 943, respectively), with varying traffic volume; and a structures' network of 161 bridges, and 356 culverts that are located within the right of way of the roads. The highway network consists of 24 highways, each highway is identified with a significant number (e.g., 102, 99, etc.), and has up to 9 sections. Each section is alphabetically named and identified by a combination of the highway ID and its alphabetical name (e.g., 102D). Figure 6.1 illustrates schematically the highway network along with the structures within the right of way. For example, highway 132 has 4 sections (A, B, C, and D); section 132A has bridges and culverts located in its right of way, 132C has culverts only, and so forth. Structures are identified according to the highway section where they are located in (e.g., if a highway section has an ID of 102A, then the structure located in the right of way of this section will be identified by 102A).

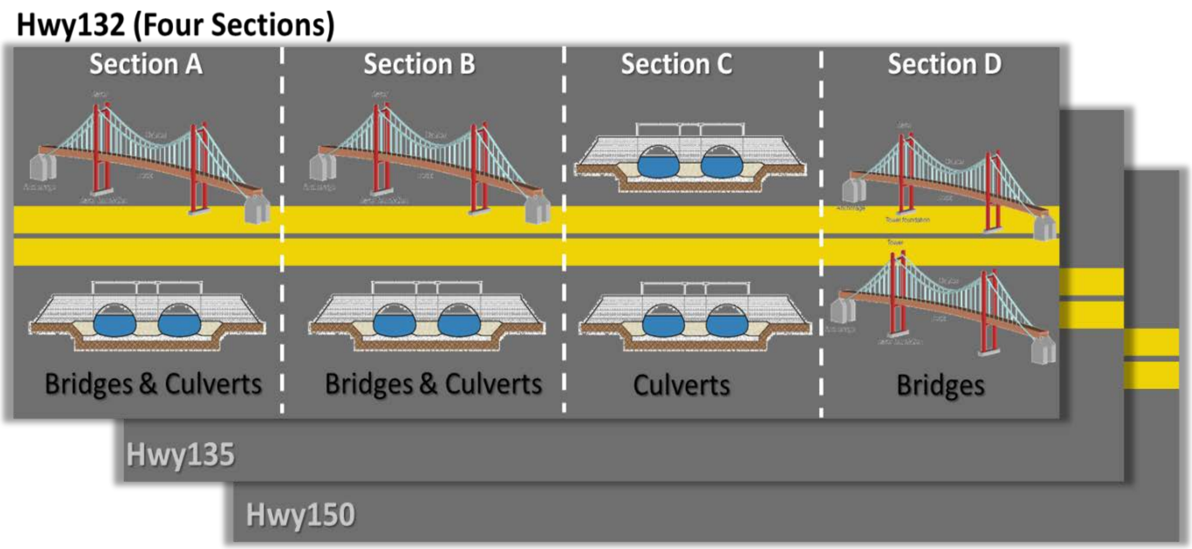


Figure 6.1 Schematic of the Highway network with the structures within the right of way

The available information for each bridge and culvert include: length, span type, clear roadway width, first year in service, condition rating, replacement cost, expected service life, etc. The condition rating for both bridges and culverts is represented in terms of a condition index CI (scaled from 0 to 100). A CI value of 0 implies an extremely critical condition, while a CI of 100 implies an excellent condition. In this research, signs are not considered due to the unavailability of information, and the assumption that they are in a good condition due to the regular maintenance and any replacement would be due to road reconstruction or catastrophic damage due to a storm or accident (Haas, 2008).

The objective in this case study is to improve the condition of the overall network of pavements and structures by deciding on which assets to be funded (network-level decision) using which rehabilitation strategy (project-level decision) in each year within a planning horizon while meeting the budget constraints. In response to the challenge (Haas, 2008), several proposals were offered by different universities and organizations. Table 6.1 summarizes these proposals in terms of the assumptions, solution methods, etc.

Despite the efforts in Table 6.1, almost none has addressed the co-location of the assets. Most of the proposals dealt with the pavements and structures separately, except for University of New Brunswick's proposal (U.N.B) that tried to tackle the mixed assets concept in one of its proposed scenarios by trading-off between asset categories. In this thesis, on the contrary, the EBCA approach is applied such that it considers the co-location of the assets while targeting equilibrium among the different spending categories.

Table 6.1 Summary of the solutions proposed to the Challenge of Haas (2008)

<table>
<tr><th rowspan="2">Proposals</th><th colspan="3">Summary of methods and results</th><th rowspan="2">Considered Mixed Assets</th></tr>
<tr><th>Pavements</th><th>Bridges</th><th>Culverts</th></tr>
<tr><td rowspan="2">ARA</td><td>▪ Roadcare software + B/C prioritization + Optimization
▪ Case 1: min cost + performance Constraint
Case 2: max performance + budget constraint
▪ Deterioration is function of IRI & SDI
▪ Plan for 20 years</td><td>▪ Replacement at end of service life
▪ CI out of 100
▪ Min CI = 40
▪ Linear deterioration</td><td>▪ Replacement at end of service life
▪ CI out of 100
▪ Min CI = 40
▪ Linear deterioration</td><td rowspan="2">No</td></tr>
<tr><td colspan="3">Results: - No indication on network condition results
- Annual Budget (millions) = $40
- Total budget $800 M (Pavements: Bridges: Culverts = 79%:17%:4%)</td></tr>
<tr><td rowspan="2">AFRICON</td><td>▪ HDM-4 software
▪ max area under the condition curve
▪ LOS is function of IRI
▪ Plan for 20 years</td><td>▪ LCCA + heuristic optimization
▪ Replacement if risk >$1 million
▪ max diff. between risk exposure w &w/o repair
▪ Risk is function of travel time and VOC</td><td>▪ LCCA + heuristic optimization
▪ Replacement if risk >$1 million
▪ max diff. between risk exposure w &w/o repair; Risk is function of travel time and VOC</td><td rowspan="2">No</td></tr>
<tr><td colspan="3">Results: - Annual Budget (millions) = $16.8 (Pavements) + $8 (Bridges + Culverts)
- Total Budget (millions) = $492 (P: B : C = 68.3% : 23.1% : 8.6%)
- From charts: IRI after 20 years ≈ (1.5-2) from average initial condition of 1.45
- From charts: average. structure condition (bridges & culverts) is 68% from average initial condition of 62%</td></tr>
<tr><td rowspan="2">STANTEC</td><td>▪ 3 types of repair
▪ IRI for present condition, SDI for future service</td><td>▪ Replacement only
▪ Linear deterioration</td><td>▪ Annual Prioritization by efficiency factor</td><td rowspan="2">No</td></tr>
<tr><td colspan="3">Results: - Annual budget (millions) = $30 (Pavements) +$13.7 (Bridges) + $2.6 (Culverts)
- Total Budget (millions) = $926 (P : B : C = 64.7% : 29.6% : 5.7%)
- All Conditions are within minimum acceptable</td></tr>
<tr><td rowspan="2">U.N.B</td><td>▪ "TAMWORTH" Optimization;
▪ Cost-effectiveness evaluation.
▪ Operational window for flexible rehab ranges
▪ 4 rehab cases: 3 cases of min cost + performance constraint, 1 case of max performance + budget constraint
▪ KPI = IRI; ignored VOC; no interest rate</td><td>▪ 4 main rehab cases: replacement only; midlife rehabilitation; elimination of very poor bridges in the first 10 years &Midlife rehabilitation; rehab & tradeoff
▪ 3 cases of min cost + performance constraint, 1 case of max performance + budget constraint
▪ KPI = BCI; linear deterioration</td><td>▪ 4 main rehab cases: replacement only; midlife rehabilitation; elimination of very poor bridges in the first 10 years &Midlife rehabilitation; rehab & tradeoff
▪ 3 cases: min cost + performance constraint; 1 case: max performance + budget constraint
▪ KPI = BCI</td><td rowspan="2">Trade-off between assets</td></tr>
<tr><td colspan="3">Results: - Avg. Budget in 20 years (millions): Case A = $28.5; B = $34.2; C=$50.87; E=$36/year
- Pavement Condition after 20 years: Case A= 80.7; B= 80.5; C= 84.1; D= 82.4
- Bridges Condition after 20 years: Case A= 58.5; B= 58.9; C= 79.4; D= 79.9)
- Culverts Condition after 20 years: Case A= 60.5; B= 60.5; C= 60.5; D= 81.0
- No indication on budgeting distribution among the different asset categories</td></tr>
</table>

Table 6.1 (Cont'd)

Proposals	Summary of methods and results: Pavements	Bridges	Culverts	Considered Mixed Assets
U of Delaware	▪ HERS-ST; max benefits; BCA ▪ Repair halfway funding period ▪ four 5-year funding periods	▪ Excel Spreadsheets ▪ Annual Prioritization by efficiency factor	▪ Annual Prioritization by efficiency factor	No
	Results: - Annual Budget (millions) = $270 (Pavements) + 0.559 (Bridges) + 0.09 (Culverts) - Total Budget (millions) = $5,412.98 (P : B : C = 99.7% : 0.2% : 0.03%) - Pavement condition maintained at average B/C of 10.82 - bridge condition maintained at CI of 60, culverts condition maintained at CI of 63			
U of W	▪ HDM-4 software; max the performance (IRI) ▪ KPI = IRI; Net Benefit = user benefits-admin. costs ▪ An Overall Asset Index (OAI) to represent the whole network; 76 groups of sections;	▪ Excel+Evolver; min Total Cost ▪ Cond. index out of 100 ▪ Min CI = 40; $CI_{20} >= CI_1$ ▪ 3 repair options; Linear deterioration ▪ 2 decision variables: repair year & type	▪ Spreadsheet schedules ▪ Cond. index out of 100 ▪ Min CI = 30 ▪ Linear deterioration	No
	Results: - Total budget (millions) = $544.858 = $303.2 (Pavements, 55.6%) + $212.85 (Bridges, 39.1%) + $28.808 (Culverts, 5.3%) - Pavements: Avg. IRI (20years) = 1.49; Initial condition (IC) = 77%; Final Condition (FC) = 77% - Bridges: Avg. CI (20 years) = 65; IC = 58%; FC = 66% - Culverts: Avg.CI (2027) = 65.02; Avg. CI (2008) = 64.9; IC = 64%; FC = 65%			
Virginia 1	▪ MATLAB; Sorting by AADT ▪ 3 cases: min user costs; agency costs; total costs; ▪ Considered rutting and IRI	NA	NA	No
	Results: - Total Budget (millions) = Case 1 (min agency costs) = $1,109; Case 2 (min user costs) = $1,221; Case 3 (min total costs) = $748 - $75M annual budget limit reduces user costs & increases agency costs due to extensive repairs; $30M annual budget limit was reasonable - Tried splitting to rural & urban using a budget of $39:$46 & $21:$54; difference bet. splitting & combined studies is moderate - No indication on network condition results			
Virginia 2	▪ Excel spreadsheets ▪ Splitted road sections to 2 groups: rural & urban ▪ Benefits =service life extension ▪ Considered IRI & SAI; Linear deterioration	NA	NA	No
	Results: - Annual Budget (millions in 2008 dollars): of $3.1 (interurban) and $2.9 (rural) - Total Budget (millions in 2008 dollars): $120 - No indication on network condition results			

6.3 Applying EBCA to Co-located Assets

Considering the co-location of the assets (pavements, bridges, and culverts) within the highway network, the proposed EBCA approach is applied at the network-level over a 5-years planning horizon (which can be extended to any number of years or funding periods), to determine the optimum rehabilitation timing for each asset, while achieving equilibrium among them. The annual available budget is assumed $50 million. However, LCCA and project-level models were developed for each category of assets: pavements; bridges; and culverts, separately then used as an input to the overall network-level model. For the pavements network, the readily developed LCCA model in Chapter 3 is used; while for the structures' network, based on the available information for the bridges and culverts, LCCA models have been developed for both with the following assumptions:

1. The condition is assumed to deteriorate linearly along the life span of the structure. The deterioration rate (DR) is determined from the expected service life (SL) of the structure, which is influenced by the road type where the structure is located in, using the following equation:

$$\text{Deterioration Rate (DR)} = \frac{100}{Expected\ Service\ Life\ (SL)} \tag{6.1}$$

For example, if a given bridge is located in a rural area, then the expected SL is 60, and consequently DR = 1.67; while, if the bridge is located in an urban area, the expected SL is 45, and thus resulting in higher deterioration rate (DR) of 2.22.

2. Two repair strategies are assumed for each structure: minor rehabilitation which improves the condition by 40%, and full replacement which results in 100% condition improvement.
3. The cost of minor rehabilitation for a given structure is assumed to be 60% of the full replacement cost.

4. Structures with average condition index (CI) above a value of 60, without rehabilitation, are not considered in the current planning horizon.

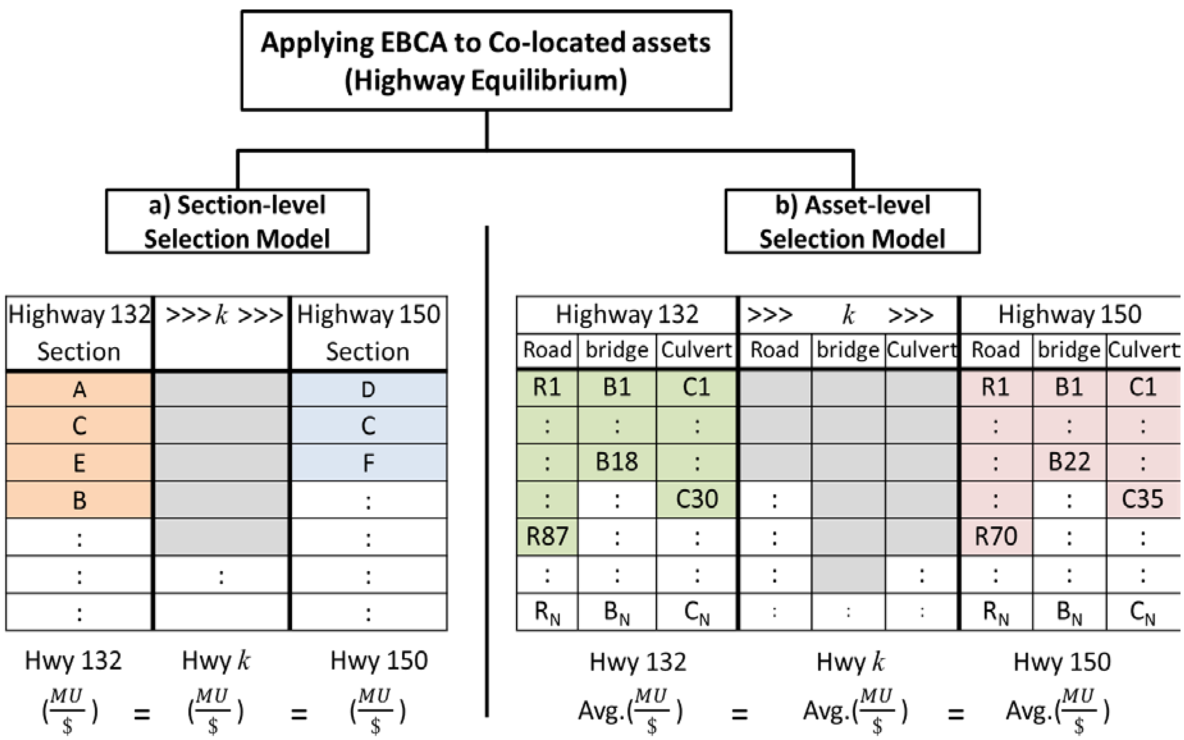
Following the proposed methodology presented earlier in Figure 5.2 (Chapter 5), first project-level analysis is done using benefit-cost ratio (BCR) analysis for bridges and culverts to determine the best rehabilitation method in all years. Afterwards, project-level decisions produced for each network of assets, are used as an input to the overall network-level model for the implementation of the proposed EBCA heuristic approach as described in the following subsection.

6.3.1 Strategies to handle Co-located Assets using EBCA Approach

The EBCA approach has been applied at two alternative levels using different strategies to achieve balance among the highways: Section-level, and Asset-level, as shown in Figure 6.2. Referring back to the consumer problem that the heuristic approach is built upon, the consumer selects number of units from each spending category till the equilibrium is achieved among these categories, and the budget is fully exhausted.

Accordingly, in the first approach “Section-level Model”, assets are grouped according to the highway where they are located in (e.g., 102), the highway section (e.g., 102A, 132B, etc.), and asset category type (pavements, bridges, culverts). This model assumes funding the entire highway section once it is selected for renewal; such that, all the pavements and structures existing in this section will be rehabilitated (e.g., selecting section 102A for rehabilitation means repairing all the assets existing in this section, excluding structures that are in acceptable condition without rehabilitation). Accordingly in this model, highways are the spending categories that compete for funding, and the sections represent the units to be selected from each; such that, a number of sections from each highway is selected that would achieve equilibrium among highways, as shown in Figure 6.2a (e.g., sections A, C, E and B are selected from highway 132; and sections D, C, and F are selected from highway 150, etc.).

In the second approach "Asset-level Model", on the other hand, assets are grouped according to the highway where they are located in (e.g., 102), and the asset category type (pavements, bridges, culverts), as shown in Figure 6.2b. In this model, pavements; bridges; and culverts asset categories are the spending categories that compete for funding. As such, a number of pavements, bridges, and culverts are selected from each asset category in each highway so that equilibrium is achieved among the highways (e.g., selecting 87 roads, 18 bridges, and 30 culverts from highway 132, and 70 roads, 22 bridges, and 35 culverts from highway 150, and so forth).



Note: Shaded cells implies assets or sections selected for renewal

Figure 6.2 Two strategies for handling rehabilitation of co-located assets

6.3.2 Section-level Model

In this model, as previously described, each highway represents a category and each section within a highway represents a unit to be selected. Thus, marginal utility per dollar gained due to the selection of any of the highways' sections is represented in terms of the average marginal utility per dollar of all assets existing in this section "Avg.MU/$_{section}$", using the following equation:

$$Avg.(\frac{MU}{\$})_{Section\ j} = \left[\begin{array}{c}\text{Weighted average of the average MU/\$ value of each category} \\ \text{of assets (pavements, bridges, culverts) within the section}\end{array}\right] \quad (6.2)$$

$$Avg.(\frac{MU}{\$})_{Section\ j} = \frac{\sum_{i=1}^{N} Avg.MU/\$_{category\ i} \times RIF_i}{N}$$

Where $Avg.MU/\$_{category\ i}$ is the average marginal utility per dollar of the assets' marginal utility per dollar values in each category *i* within section *j*, and *N* is the number of categories available. RIF_i is an assumed relative importance factor that captures the decision maker's preferences in differentiating the importance of the asset categories (e.g., pavements versus bridges versus culverts). RIF_i can be mathematically determined using the following equation:

$$RIF_i = \frac{Total\ Replacement\ Cost\ of\ Category_i}{Total\ Replacement\ Cost\ of\ the\ whole\ Network} \quad (6.3)$$

To determine optimum funding decisions, the steps of the generic heuristic process previously described in Figure 5.3 (Chapter 5) are applied, yet with some modifications to accommodate this model. Thus, for each year in the planning horizon:

1. Group unfunded assets according to the highway (e.g., 102, 105, 132, etc.), then according to the section where they are located in (e.g., 102A, 102B, etc.), then according to asset type (pavements, bridges, culverts);

2. List the performance improvement (difference in condition before and after repair) and the renewal cost for each asset based on the LCCA calculations, assuming all assets will be funded this year. In order to unify the scale of performance improvements across the different asset categories, the pavements' condition in terms of IRI is converted to a condition index (CI) scaled (0-100) similar to the structures' condition index, where 100 represents best condition and 0 represents extremely critical condition;
3. Compute the MU/$ for each asset by dividing performance improvement with renewal cost. The performance improvement of each asset, in each category, is multiplied by the size factor (SF, 1 to 10), previously described in Chapter 3 (Equation 3.9), to take into consideration the differences in the assets' sizes. For the structures, the SF has been modified to consider the full replacement cost of the asset rather than the area to roughly represent the size of the structure under consideration;
4. Compute the average MU/$ for each highway section (Avg.MU/$_{section}$);
5. Sort sections in each highway in a descending order according to the Avg.MU/$_{section}$; and
6. Select sections for funding starting from the top of the sorted list of each highway till the Avg.MU/$_{section}$ value of the last selected section in each highway is almost equal, and the budget for this year is fully exhausted. Move unfunded sections beyond this equilibrium point to the next year in the planning horizon.

   Proceed to step 1 for the analysis of the next year, until last year in the planning horizon.

In this model, the number of integer variables is 24 representing the number of highways, in addition to two constraints: the variable value (number of selected sections in a given highway) is less than or equal the total available; and the total costs of all selected sections exhausts the available budget. To satisfy the equilibrium condition, the objective function is set to minimize the variance across the MU/$ values across the highways. The $MU/\$_{Hwy}$ of a given highway is the $Avg.MU/\$_{section}$ value of the last selected section in this highway. Mathematically, the formulations of the variables, objective function, and constraints are represented by equations 6.4 to 6.7.

Variables: K variables, each representing the number of sections (X_k) selected from the sorted list in each highway *k*;

X_k, X_{k+1}, …………….X_K (6.4)

Objective Function: minimize variance across $MU/\$_{highway}$ values that associate the last selected section in the number of sections X_k in each highway (*k*).

Minimize Variance ($MU/\$_{X_k,Hwy\ k}$, $MU/\$_{X_{k+1},Hwy\ k+1}$,….., $MU/\$_{X_K,Hwy\ K}$) (6.5)

Constraints:

$\sum Costs \leq Budget$ (6.6)

$X_k \leq m_k$, where *m* is the number of sections available in highway (*k*) (6.7)

Due to the simplicity of this model with respect to the number of variables and solution space, it has been applied manually to the case study data. The summary of the results along the 5-year planning horizon is presented in Table 6.2. It shows in each year: the sections selected from each highway, Avg. MU/$ of the last section selected in each highway, the costs associated with each highway, and the total annual cost. In the last row of the table, a summary of the number of assets selected from each category, the % overall condition improvement of each asset category, and the % budget utilized by each category over the five years planning horizon, is presented.

Table 6.2 Summary of the 5-year plan results (Section-level model)

	Highways	Sections to be repaired	Avg.MU/$ of last selected section	Total Cost /Highway	Total Annual Cost
Year 1	HWY-132	C	0.167	3,189,979	
	135	G	0.210	2,128,118	
	138	A	0.169	3,617,818	
	150	A	0.200	9,571,743	
	231	B	0.179	8,927,313	
	237	C, D	0.192	5,282,759	
	6	A, D, E, G	0.165	7,983,619	
	96	A, B	0.251	11,412,103	49,163,633
Year 2	132	A	0.129	5,399,994	
	138	B	0.118	4,472,719	
	150	B, C	0.110	15,160,917	
	195	A	0.114	6,350,683	
	231	A	0.114	5,711,810	
	237	A	0.129	3,137,437	
	96	C	0.130	1,775,188	
	99	A	0.116	13,384,805	49,300,065
Year 3	102	A	0.074	10,101,784	
	132	B	0.072	9,543,267	
	135	A	0.091	2,194,731	
	141	A, B	0.074	10,821,931	
	237	B	0.072	5,711,810	
	6	B, C	0.077	1,294,700	
	72	A, C	0.075	13,985,988	
	96	D	0.083	5,284,489	49,486,068
Year 4	132	D	0.047	15,291,688	
	135	C, D, E, F	0.048	30,752,541	
	177	E	0.046	4,687,817	
	78	C	0.050	11,323,632	49,153,909*
Year 5	105	A	0.022	6,934,783	
	72	D, E	0.021	25,941,903	
	75	A, C	0.022	33,641,474	49,706,239

Summary of results:
Number of assets selected for rehabilitation: Pavements (847), Bridges (69), Culverts (108)
Condition Improvement: Pavements (15.7%), Bridges (27.84%), Culverts (19%)
% Budget Utilization: Pavements (55%), Bridges (39%), Culverts (6%)

*Note: * total budget may be not totally consumed*

Table 6.3 shows the MU/$ values of highways with sections that has been selected for renewal among the 24 available highways in each year, with the variance across the values in the last row of the table. It can be noted from the table and the variance values that the MU/$ values across the highways are very close, thus achieving balance among the different highways.

Table 6.3 MU/$ values of each highway in each planning year (Section-level model)

Highway ID	MU/$ across highways				
	Year1	Year2	Year3	Year4	Year5
102			0.074		
105					0.022
132	0.167	0.129	0.072	0.047	
135	0.210		0.091	0.048	
138	0.169	0.118			
141			0.074		
144					
150	0.200	0.110			
177				0.046	
195		0.114			
231	0.179	0.114			
237	0.192	0.129	0.072		
285					
3					
6	0.165		0.077		
66					
72			0.075		0.021
75					0.022
78				0.050	
9					
90					
93					
96	0.251	0.130	0.083		
99		0.116			
Variance	0.00073	5.5E-05	3.7E-05	1.6E-06	1.4E-07

Note: a cell with no value means none of the sections in the corresponding highway were selected for rehabilitation

6.3.3 Asset-level Model

In this model, assets are selected from each asset category in each highway to achieve equilibrium among highways. Thus, the objective function is set to target equality among the average marginal utility per dollar across highways ($Avg.(\frac{MU}{\$})_{Hwy\ k}$), as shown in equation 6.8.

$$Avg.(\frac{MU}{\$})_{Hwy\ k} = \frac{\sum_{i=1}^{N} MU/\$_{category\ i} \times RIF(1)_i \times RIF(2)_i}{N} \qquad (6.8)$$

Where $MU/\$_{category\ i}$ is the marginal utility per dollar of the last selected asset in category i, N is the number of categories available (For the three asset categories in this case study, N=3). $RIF(1)_i$ and $RIF(2)_i$ are relative importance factors used to capture the decision maker's preferences in differentiating the importance of different asset categories (e.g., pavements versus bridges versus culverts). Table 6.4 and 6.5 shows an example highway demonstrating the computations of both RIFs.

Table 6.4 Example section showing $RIF(1)_i$ calculations

	Replacement Cost			$RIF(1)_{\mathbf{P}}$	$RIF(1)_{\mathbf{B}}$	$RIF(1)_{\mathbf{C}}$
	Pavements	Bridges	Culverts			
Highway$_{102}$:	$P_{102} = \sum \$$ All assets :	$B_{102} = \sum \$$ All assets :	$C_{102} = \sum \$$ All assets :	**P/T** Same for all sections	**B/T** Same for all sections	**C/T** Same for all sections
Total	**P** = $\sum \$$	**B** = $\sum \$$	**C** = $\sum \$$	**T** = P + B + C		

Table 6.5 Example section showing $RIF(2)_i$ calculations

	Replacement Cost			$RIF(2)_{\mathbf{P}}$	$RIF(2)_{\mathbf{B}}$	$RIF(2)_{\mathbf{C}}$
	Pavements	Bridges	Culverts			
Highway$_{102}$	$P_{102} = \sum_{\text{All assets}} \$$	$B_{102} = \sum_{\text{All assets}} \$$	$C_{102} = \sum_{\text{All assets}} \$$	P_{102} / Max_P	B_{102} / Max_B	C_{102} / Max_C
:	:	:	:	:	:	:
Max =	Max_P	Max_B	Max_C			

Similarly to the section-level model, to determine the optimum funding decisions, the steps of the generic heuristic process, previously described in Figure 5.3 (Chapter 5), are applied, yet with some modifications. Thus, for each year in the planning horizon:

1. Group unfunded assets according to the highway where they are located in (e.g., 102, 105, 132, etc.), then group them according to the asset category type (pavements, bridges, culverts);
2. List the performance improvement (difference in condition before and after repair) and the renewal cost for each asset based on the LCCA calculations, assuming all assets will be funded this year. Similarly to the section-level model, in order to unify the scale of performance improvement across the different asset categories, the pavements' condition in terms of IRI is converted to a condition index (CI) scaled (0-100) similar to the structures' condition index, where 100 represents best condition and 0 represents extremely critical condition;
3. Compute the Marginal utility per dollar (MU/$) for each asset by dividing the performance improvement by the renewal cost. The performance improvement of each asset, in each category, is multiplied by the size factor (SF, 1 to 10), previously described in Chapter 3 (Equation 3.9), to take into consideration the differences in assets' sizes. SF for pavements is function of the road section area, while for the structures is function of the asset's full replacement cost.

4. Sort the assets in a descending order, according to the MU/$; and
5. Select assets for funding starting from the top of the sorted list of each category in each highway, till the *Avg.MU/$*$_{Hwy}$ (Equation 6.8) of each highway in the network is almost equal, and the budget for this year is fully exhausted. Move unfunded assets beyond this equilibrium point to the next year in the planning horizon.

   Proceed to step 1 for the analysis of the next year, until last year in the planning horizon.

To facilitate finding the optimum solution without trial and error, the simplified optimization model (section 5.3.2, Chapter 5) is used and solved using Genetic algorithm of Excel Add-in Evolver (Figure 6.3). The model has 72 integer variables (3 asset categories x 24 highways), in addition to two constraints: the variable value (number of selected assets in a category) is less than or equal the total available; and the total costs of all selected assets exhausts the available budget. To satisfy the equilibrium condition, the objective function is set to minimize the variance across the Avg.MU/$ values across the highways. To make sure that the Avg.MU/$ values are equal, Equality Factors are used, as follows:

$$\text{Equality Factor } (EF_{k,k+1}) = \frac{Avg.MU/\$_{Hwy\ k+1}}{Avg.MU/\$_{Hwy\ k}} \qquad (6.9)$$

In this case, the number of equality factors is dependent on the number of highways that the model is targeting equilibrium among them, thus, if the number of highways is K, then the number of equality factors is K-1. Since the number of highways is 24, then the number of the needed equality factors is 23. Mathematically, the formulations of the variables, objective function, and constraints are represented by equations 6.10 to 6.14.

Variables: N × K integer variables, each representing the number of assets (X_{ik}) selected from each sorted category *i* in each highway *k*;

$$X_{ik}, X_{ik+1}, \ldots\ldots\ldots\ldots\ldots X_{NK} \qquad (6.10)$$

Objective Function: minimize variance across Avg. MU/$ highway values that associate the number of assets X_{ik} selected from category *i* in each highway *k*;

$$\text{Minimize Variance } (Avg.\,MU/\$_{X_{ik},Hwy\,K}, \ldots\ldots, \text{Avg.}\,MU/\$_{X_{NK},Hwy\,K}) \qquad (6.11)$$

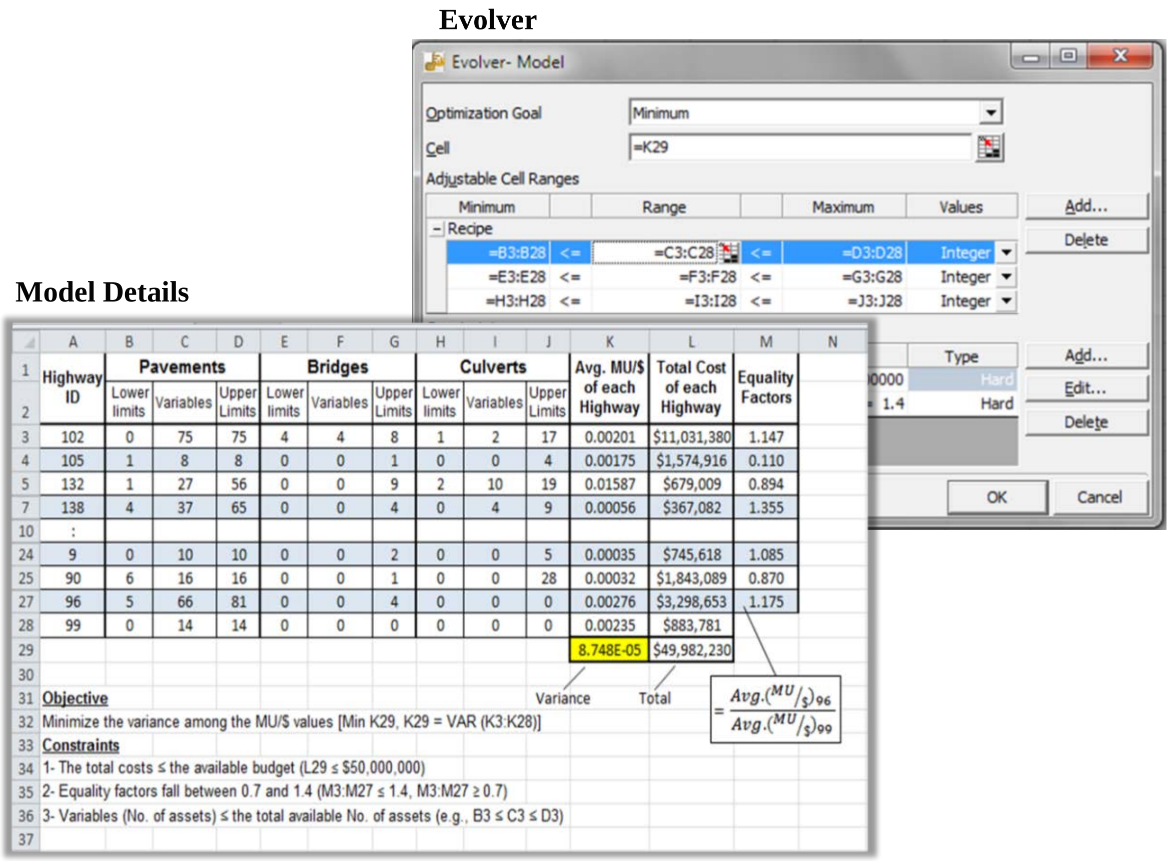
Constraints:

$$\sum Costs \le Budget \qquad (6.12)$$

$$0.7 \le EF_{k,k+1} \le 1.4, \text{ where } k = 1, 2, \ldots\ldots, K\text{-}1 \qquad (6.13)$$

$$X_{ik} \le m_{ik}, \text{ where } m \text{ is the number of assets available in category } (i) \text{ in highway } (k) \qquad (6.14)$$

In order to facilitate finding an optimum solution in such large-scale problem, the equality factors are constrained to lie in a more relaxed range between 0.7 and 1.4. Figure 6.3 is showing the application of the previous formulations to the network of assets, using Excel Add-in Evolver. The summary of the results along the 5-year planning horizon is presented in Table 6.8. It shows the number of assets selected from each category of assets; % selected assets from each category; the annual cost per category and total annual cost that almost fully exhaust the $50 million assumed budget; the % that each category of assets consumed from the budget; the condition before and after rehabilitation, and the % condition improvement. The pavements condition is represented in terms of IRI, while the structures' condition is in terms of CI.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Highway ID	Pavements			Bridges			Culverts			Avg. MU/$ of each Highway	Total Cost of each Highway	Equality Factors
2		Lower limits	Variables	Upper Limits	Lower limits	Variables	Upper Limits	Lower limits	Variables	Upper Limits			
3	102	0	75	75	4	4	8	1	2	17	0.00201	$11,031,380	1.147
4	105	1	8	8	0	0	1	0	0	4	0.00175	$1,574,916	0.110
5	132	1	27	56	0	0	9	2	10	19	0.01587	$679,009	0.894
7	138	4	37	65	0	0	4	0	4	9	0.00056	$367,082	1.355
10	:												
24	9	0	10	10	0	0	2	0	0	5	0.00035	$745,618	1.085
25	90	6	16	16	0	0	1	0	0	28	0.00032	$1,843,089	0.870
27	96	5	66	81	0	0	4	0	0	0	0.00276	$3,298,653	1.175
28	99	0	14	14	0	0	0	0	0	0	0.00235	$883,781	
29											8.748E-05	$49,982,230	

31 **Objective**
32 Minimize the variance among the MU/$ values [Min K29, K29 = VAR (K3:K28)]
33 **Constraints**
34 1- The total costs ≤ the available budget (L29 ≤ $50,000,000)
35 2- Equality factors fall between 0.7 and 1.4 (M3:M27 ≤ 1.4, M3:M27 ≥ 0.7)
36 3- Variables (No. of assets) ≤ the total available No. of assets (e.g., B3 ≤ C3 ≤ D3)

Figure 6.3 Network-level optimization model details (Asset-level model)

It can be noted from Table 6.6 that the EBCA approach, similar to the common practice, has allocated more money to the road sections than the structures, within the highway network, within the 5 years planning horizon. Table 6.7 shows the achieved average marginal utility per dollar values (MU/$) of each highway within the 5-years planning horizon. The last row in the table shows the achieved minimum variance across the MU/$ values in each year. An average MU/$ value of zero for any given highway in any given year entails that none of the assets (pavements, bridges, and culverts) were selected for renewal in this highway.

Table 6.6 Summary of the 5-year plan results (Asset-level model)

		Pavements	Bridges	Culverts	Total
Money Spent (Millions)	Year 1	$13.15	$33.27	$3.50	$49.91
	Year 2	$21.15	$28.59	$0.24	$49.97
	Year 3	$30.77	$18.04	$1.17	$49.98
	Year 4	$40.38	$9.06	$0.55	$49.99
	Year 5	$23.69	$23.18	$3.12	$49.99
	Total	$129.14	$112.13	$8.58	$249.85
% out of the total budget		52%	45%	3%	
No of Assets		936	85	97	
% of Network repaired		72%	53%	27%	
Condition before repair		1.7	53.7	58.32	
Condition after repair		1.4	72.14	68.49	
% Improvement		17.65%	34.34%	17.44%	

A brief comparison between section- and asset-level models is demonstrated in Table 6.8, to compare results and to highlight the possible pros and cons of each. It can be noticed from Table 6.8, that both models are comparable, however, the asset-level model allocated money to more number of assets in total, achieved better overall performance across all the asset categories, and almost fully exhausted the budget available. However, in the section-level model, considering all the assets that are co-located in the same section for rehabilitation (excluding assets that are in acceptable condition without rehabilitation in the planning horizon under study) can potentially reduce social costs that associate rehabilitation works (e.g., time delay, disruption, noise, etc.) due to the single visit of a highway section within the planning horizon. The asset-level model, on the other hand, may lead to higher socials costs as it might involve revisiting a highway section multiple times within the planning horizon.

In essence, the implementation of the EBCA approach on the mixed assets case study confirms its applicability on large-scale problems with different types of assets. It considered the co-location of assets using two alternative approaches with the objective of achieving a strategic balance among different highways.

Table 6.7 Average MU/$ values of each highway in each planning year (Asset-level model)

Highway ID	Average MU/$ across highways				
	Year1	Year2	Year3	Year4	Year5
102	0.0002	0.0273			0.0047
105	0.0173	0.0010			0.0000
132	0.0073				0.0018
135	0.0147		0.0004		0.0048
138	0.0142	0.0136	0.0063	0.0000	0.0024
141	0.0046	0.0000	0.0004		0.0000
144	0.0090			0.0004	0.0000
150	0.0103		0.0007	0.0001	0.0027
177	0.0243	0.0023	0.0006	0.0028	0.0001
195	0.0018				0.0002
231	0.0037				0.0014
237	0.0003	0.0078			0.0003
285	0.0009	0.0006			0.00001
3				0.0695	0.00001
6	0.0001		0.3152	0.0000	0.0499
66					0.0169
72	0.0010				0.0458
75	0.0019	0.0015	0.3352	0.0204	0.0057
78	0.0001	0.0002	0.0106		
9			0.0534		0.0000
90	0.00001		0.1153		
93			0.0001		0.0067
96			0.0427		0.0068
99	0.0003	0.0002			0.0115
Variance	4.91E-05	7.02E-05	1.38E-02	5.73E-04	1.82E-04

Note: a cell with no value means none of the assets (pavements, bridges, and culverts) were selected for renewal in this highway

Table 6.8 Comparison between Section- and Asset-level models

		Section-level Model	Asset-level Model
Number of assets selected	**Pavements**	847	936
	Bridges	69	85
	Culverts	108	97
	Total	1024	1118
Condition Improvement (%)	**Pavements**	15.7	17.65
	Bridges	27.84	34.34
	Culverts	19	17.44
% Overall budget utilized		98.72%	99.94%
Pros		– Reduce social costs during rehabilitation works (one visit) – Smaller solution space due to the small number of variables	– Almost fully exhausts the available budget – Larger number of assets are selected – Higher overall improved condition
Cons		– May have leftover funds	– Requires multiple visits to the same highway section within the planning horizon (more social costs)

6.4 Conclusion

In this chapter, the proposed EBCA approach has been applied to a whole network of assets where different types of assets are co-located, by targeting equilibrium at two alternative levels (section-level, and asset-level). At the section-level, number of sections from each highway is selected to achieve equilibrium among the highways. Once a section is selected, all of the assets in this section will be repaired (structures that are in acceptable condition without rehabilitation are excluded). At the asset-level, on the other hand, number of assets from each asset category (pavements, bridges, and culverts) is selected in each highway to achieve equilibrium among the highways. The results have proved the applicability of the proposed approach to handle infrastructure funding problems where different types of assets are co-located. Also it affirmed its capability of handling large-scale problems, as it has dramatically reduced the solution space by grouping the assets into categories with respect to different criteria, and thus has reduced the number of variables. As opposed to the existing approaches that typically apply sophisticated mechanisms which try random combinations of asset selections and funding levels (with no structured strategy) to maximize benefit, the proposed approach help arrive at optimum decisions by targeting equilibrium among the different expenditure categories in a simple, practical, and structured way.

Conclusion

7.1. Conclusion

This research presents an effort to improve infrastructure fund-allocation decisions. It overcomes the shortfalls of the existing fund-allocation methods that either use ranking methods to prioritize assets using subjective criteria (e.g., age, condition), and do not consider alternative funding scenarios; or apply sophisticated optimization mechanisms that try random combinations of asset selections and funding levels with no structured strategy or justification behind the decisions. To arrive at optimum funding decisions, while being supported with solid economic justification, this research adopted well-established theories from the science of Microeconomics that relate to Consumer Theory and Behavioural Economics.

To adopt the consumer theory in the infrastructure domain; the basic premise of this research is the analogy between a consumer who has a limited income to spend on various expenditure categories, and a public agency with a limited budget, from tax payers' money, to allocate to various renewal (rehabilitation) expenditures. Using the consumer theory concepts of equal marginal utility per dollar and indifference curves, a new decision support system was developed with two components: (1) a heuristic procedure EBCA that enhances the traditional benefit-cost analysis (BCA) by targeting equilibrium among the different renewal expenditure categories, using the law of equal marginal utility per dollar, to maximize the return over the allocated tax payers' money; and (2) a visual what-if analysis too inspired by the economic indifference maps concept to help study the sensitivity of decisions under any imposed changes.

An effort was first made to validate the applicability of adopting the consumer theory concepts in the infrastructure fund-allocation problem, by testing the optimum results obtained for two real case studies, using mathematical optimization, with respect to the law of equi-marginal utility per dollar.

The two case studies relate to two asset networks of pavement sections, and building components. The analysis proved that the tested microeconomic concept applies perfectly to the infrastructure domain and the optimum decisions are achieved at an economic balance (equilibrium) among the different expenditure categories. This testing procedure can be used as a standalone benchmark test to examine the quality of any fund-allocation mechanism to confirm whether the obtained funding decisions maintain an equilibrium status across the different expenditure categories or not.

To demonstrate the features of the new decision support system, it was applied to a building case study at the network-level, and the optimum decisions resulting from the EBCA heuristic approach were compared against the results using the existing methods in the literature (mathematical optimization, genetic algorithm, simple ranking). The comparison showed that the EBCA approach has produced better overall condition than the genetic algorithm and simple ranking approaches, and comparable solution to the mathematical optimization. The EBCA approach, however, has arrived at optimum deicsions in a simple, structured, and justifiable way as opposed to the mathematical optimization model. Moreover, it has the benefit of being suitable to be applied manually or using a simple optimization model that has dramatically reduced the solution space, and thus is more suitable for large-scale problems. The new visual what-if analysis tool was applied as well to the case study data. It extends the concept of the indifference curves to visualizing all possible decisions with both total utility and total cost associated with each decision. It facilitates studying visually the sensitivity of decisions under any imposed changes through a simple What-If analysis. Also an effort to extend the visual maps from 2D to multi-dimensional maps has been presented, in order to facilitate studying decisions across multiple asset/expenditure categories.

Due to the capability of the new EBCA heuristic approach in dramatically reducing the solution space, it has been applied to a larger-scale case study where multiple assets, pavements; bridges;

culverts, are co-located and competing for funding. The EBCA approach has been applied using two alternative stratgies (section-level, and asset-level). In the section-level strategy, number of sections from each highway is selected to achieve equilibrium among the highways. Once a section is selected, all of the assets in this section will be repaired (excluding assets with acceptable condition, without rehabilitation, in the planning horizon under study). In the asset-level strategy, on the other hand, number of assets from each asset category (pavements, bridges, and culverts) is selected in each highway to achieve equilibrium among the highways. The results proved the applicability of the proposed approach in infrastructure funding problems where different types of assets are co-located. Also it affirmed its capability of handling large-scale problems, as it dramatically reduced the solution space by grouping the assets into categories with respect to different criteria, and thus reducing the number of variables.

To examine the influence of behavioural aspects on infrastructure rehabilitation decision-making process, this research has tackled the science of behavioural economics that lies under the umbrella of Microeconomics. It focused, however, on the most common behavioural perspective "Loss-aversion" and adapted it into the infrastructure fund-allocation problem by framing the problem from a loss perspective. Such that, the objective is set to minimizing losses that result from delaying or not repairing assets rather than the typical approach of maximizing gain. Using a pavement case study, a detailed life cycle cost analysis model was developed and three mathematical optimization experiments (one gain-based model and two loss-based models) with different objective functions and perspectives were carried out. The results have showed that the experiments that represented either gain or loss with respect to the asset condition (authority's perspective) are comparable, as they consider the same point of view. While the loss-based experiment that has considered the users' loss (increased vehicle operating costs), has resulted in a completely different fund-allocation strategy than the other experiments. Incorporating behavioural aspects into asset management decisions, therefore, can better reflect the preferences of all stakeholders, and can potentially improve infrastructure renewal decisions.

In essence, infrastructure funding problem is an important economic decision, and this research is aiming at improving this crucial problem by integrating the two worlds of Microeconomics and infrastructure asset management. Such integration will help provide optimum funding decisions supported with sound economic justification, and thus can help increase the credibility of funding methods to the society and the public, and justify the spending of tax payer's money on infrastructure rehabilitation projects.

7.2. Research Contributions

This research has the potential to improve infrastructure rehabilitation decisions, inspired by the broad array of concepts available in the science of Microeconomics. It contributes to the body of knowledge with the following contributions:

- **Microeconomic benchmark test for fund-allocation decisions:** This benchmark test can be used as a standalone testing took to economically justify, and examine the quality of any fund-allocation mechanism. It tests whether an equilibrium state is maintained or not at which fair and equitable allocations are achieved.
- **EBCA Heuristic Approach:** This enhanced benefit-cost analysis approach optimizes decisions by targeting equilibrium among the different renewal expenditure categories in a practical structured way, while providing solid economic justification behind funding decisions. It also dramatically reduces the solution space in comparison with the existing methods, and thus is more suitable for large-scale problems.

- **Visual What-if analysis sensitivity tool:** This new powerful graphical tool visualizes all possible funding decisions with total utility and total cost associated with each, and thus can readily facilitate decisions in case of tied situations. Moreover, it determines visually the impact of changes in the budget limits on the decision and on the achievable utility level, through a simple What-If analysis.

- **Incorporation of behavioural aspects into infrastructure decision-making**

  In an effort to capture behavioural aspects in the infrastructure fund-allocation problem, this research adapted the most common behavioural perspective "loss-aversion" into the infrastructure problem. It investigated the difference between gain and loss framing perspectives in the allocation of rehabilitation funds with respect to different stakeholders (authority and users). It has proved that incorporating behavioural aspects can lead to different funding strategies that may better reflect the different stakeholders' preferences, and thus can improve infrastructure fund-allocation decisions.

- **Co-location of mixed assets in the infrastructure decision-making**

  This research presented an effort that justifies the coordination of rehabilitation work of co-located assets. The proposed EBCA heuristic approach has been applied to a highway network that consists of different types of assets that are co-located. The approach has been applied using two alternative strategies. The results showed that the proposed approach can handle such large-scale infrastructure problems where different categories of assets exist, as it dramatically reduces the solution space along with a solid economic justification.

7.3. Future Research

This research presented an effort on integrating the two worlds of Asset management and Microeconomics. However, with continued research, the proposed decision support tools can be extended to improve the economics of the multi-billion dollar business of infrastructure management, and provide wiser spending of tax payer's money on infrastructure rehabilitation. Thus, the following areas are recommended for further study:

- Integrating multiple decision benefits (or utilities), as opposed to this research that defined benefits only in terms of the physical asset improvement;
- Considering multiple stakeholders' point of view while defining the benefits and costs in the EBCA approach, rather than only considering the perspective of one stakeholder (authority or asset owner);
- Applying the proposed concepts at the strategic level to help governments allocate budgets while achieving equilibrium among different infrastructure services, and being able to justify decisions to the public;
- Expanding the present research to study other behavioural economic aspects in asset management decision making problems. For example, the concept "Pockets of money" (Table 2.3) can be used to set pre-defined budget constraints on specific spending categories and not to exceed or mix the budgets available in each pocket. Also, the concept "choice architecture" can be used to avoid allocating money to very high or very low rehabilitation strategies. Using the proper combination of these aspects can better reflect the preferences and behaviours of all stakeholders, thus improving policy making of infrastructure management;
- Considering the performance and/or social losses associated with the government strategic budgeting decisions regarding new construction versus rehabilitation projects, since spending money on constructing a new project is accompanied by a missed opportunity to rehabilitate a given infrastructure asset, and vice versa.;
- Experimenting with the presented behavioural economic concepts in this research in the domain of construction management (e.g., resource management, time-cost trade-off analyses), as

considering loss in terms of project time extension and/or cost overruns alone may not be sufficient. This is because the industry is being exposed to many factors that affect the behavioural expectations of stakeholders, including: increase in automation; higher safety and environmental standards; and spread of personal communication tools. The impact of such factors needs to be analysed and considered to properly represent decision implications, and thus introduce better ways to resolve construction constraints; and

- Developing fund-allocation optimization models using the theory of Demand and Supply curves by considering public users' satisfaction. Figure 7.1 shows an initial effort on adopting the concept of demand and supply in the infrastructure rehabilitation problem.

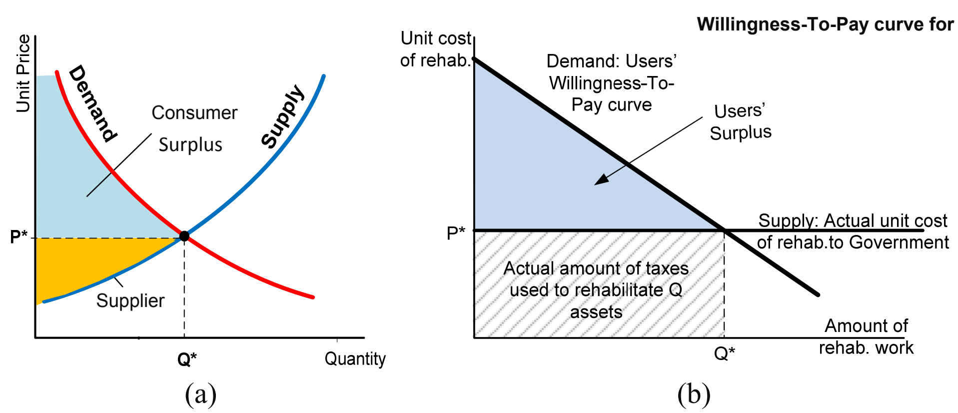


Figure 7.1 Adopting Demand and Supply Curves in the infrastructure problem

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Appendix I

Mathematical proof of the equi-marginal-utility concept (Chugh, 2014)

Assume a consumer is willing to spend money on two products *x* and *y* with unit prices ($/unit) P_1 and P_2 respectively. The consumer's objective is to maximize his satisfaction/utility $U(x, y)$ while being subjected to limited available budget *B*. Therefore, the objective function is to maximize:

$$\text{Utility} = U(x, y) \quad \text{(A.1)}$$

Subject to the budget constraint:

$$B = P_1 \,.\, x + P_2 \,.\, y \quad \text{(A.2)}$$

Using Lagrange method, the previous equation can be rewritten as follows:

$$\mathbf{L} = U(x, y) + \lambda\,(B - P_1 \,.\, x - P_2 \,.\, y), \quad \text{where } \lambda \text{ is the Lagrange multiplier} \quad \text{(A.3)}$$

Taking derivatives on the L function, we obtain the so called first order conditions with respect to *x*, *y*, respectively as follows:

$$\partial \mathbf{L}/\partial x = \partial U/\partial x - \lambda\, P_1 = 0 \quad \text{, where } \partial U/\partial x = \text{marginal utility for item } x \quad \text{(A.4)}$$

$$\partial \mathbf{L}/\partial y = \partial U/\partial y - \lambda\, P_2 = 0 \quad \text{, where } \partial U/\partial y = \text{marginal utility for item } y \quad \text{(A.5)}$$

By solving equation A.4 for the multiplier λ, the value of λ can be obtained as follows:

$$\lambda = \frac{\partial U/\partial \mathrm{x}}{P_1} \quad \text{(A.6)}$$

By substituting the value of λ in equation A.5, the following equation is obtained,

$$\partial U/\partial y - \frac{\partial U/\partial x}{P_1} P_2 = 0 \qquad \text{(A.7)}$$

From equation A.7, the following can be reached:

$$\frac{(\partial U/\partial x)}{P_1} = \frac{(\partial U/\partial y)}{P_2} \text{ , or } \left(\frac{Marginal\ Utility}{price}\right)_1 = \left(\frac{Marginal\ Utility}{price}\right)_2 \qquad \text{(A.8)}$$

Therefore, from Equation A.8, the optimal allocation of money that maximizes the total utility is achieved when the last unit purchased from each product yields the same marginal utility to price ratio ($\frac{\partial U}{\$}$).

Appendix II

Terms of Reference For

The ICMPA7 Investment Analysis and Communication Challenge for Road Assets

'THE CHALLENGE'

Introduction

Background

The 6th International Conference on Managing Pavements (ICMP6) introduced a new dimension to the series in terms of a "Pavement Management Investment Analysis Challenge".

The Challenge was initiated with a worldwide Call for Expressions of Interest, and 16 teams from North America, South Africa, United Kingdom, New Zealand, and Australia were subsequently invited to carry out an analysis and recommend strategies for managing a defined network of interurban and rural roads.

The overall purpose of the Challenge, as articulated by Laurie Dowling, Chair of the Panel, was to enhance the educative benefits of ICMP6 by providing an opportunity for asset management professionals to demonstrate how good practice could be applied within a range of available procedures and systems.

More specifically the Challenge aimed to identify, encourage, and disseminate good practice in pavement management, to encourage innovation and to provide a forum and documentation illustrating state-of-the-art pavement management systems.

Response to the Challenge, both in terms of the quality of submissions and the interest from conference participants, proved it to be an unqualified success. The final conference proceedings provide details.

A New Challenge

The success of ICMP6 was a key factor in a decision by the organizers of the 7th International Conference on Managing Pavement Assets (ICMPA7), to develop a new Challenge. Since ICMPA7 was still to have a main focus on pavement assets but also to include associated road assets, the Steering Committee recommended an expanded scope for the Challenge

In addition, the Committee suggested a strong emphasis be placed on communicating the message – in other words, both carrying out the analysis and communicating the results in a convincing, comprehensible manner to the "clients".

Scope of the ICMPA7 Challenge

The ICMP6 Pavement Management Investment Analysis Challenge involved a defined network of highly trafficked to lightly trafficked interurban and rural roads. Respondents were encouraged to apply a methodology used in practice as decision support similar to that required by road network investment decision makers

The ICMPA7 Challenge builds upon the ICMP6 Challenge, but is also expanded to incorporate a variety of assets within the right-of-way in addition to pavements. A capital cost, preventive maintenance, rehabilitation, and reconstruction investment analysis will be required that considers pavements, bridges, culverts, and signs. The network will once again be comprised of interurban roads and rural roads with a wide range of traffic volumes. However, in this Challenge the number of lanes is variable. In addition, a budget will not be prescribed. Instead challenge respondents will determine optimum investment levels based on trigger levels of acceptability.

Major emphasis is to be placed on communicating the message to the informed manager as well as to the non-technical or non-administrative such as the public.

General Features of the Area

The network of roads subsequently described generally covers an area of relatively flat to slightly rolling terrain. Subgrade soils are mostly clays, ranging from low to high plasticity. The climate is in a dry, high freeze zone (as defined in the Long Term Pavement Performance, LTPP, study in the Strategic Highway Research Program). Drainage is good over most of the area, with occasional flooding risk in a few low places.

The Road Authority

The road authority is in the state of "Icompa", although it can be recognized that extensive use has been made of data and information from the Province of Alberta. However, organizers of the Challenge have taken the liberty of modifying certain data and information, adding new elements, providing their own technical and cost estimates where available information does not exist, and generally trying to arrange the terms of reference so that respondents can effectively demonstrate state-of-the-art practices in their submission.

The Network to be Analyzed

The network of assets to be analyzed is composed of pavements, bridges, culverts, and signs. The features of each asset are discussed in the following sections. Samples of the spreadsheets for each asset are provided in Appendices, as subsequently described. Challenge respondents to the Call for

Expressions of Interest who are invited to prepare a submission will be provided with a website link to the full database.

It should be emphasized that while considerable effort has gone into preparing the database, it is certainly not perfect, and assumptions will undoubtedly be required where inconsistencies appear. However, since the Challenge involves a network level investment and communication challenge, any specific inconsistencies in the database should not impact on the overall results.

Pavement Network

The pavement network is comprised of a total of 1293 road sections spanning 3240 km, covering two road classes, and varying in traffic use, surface age, and condition. The scope of the pavement network is illustrated in Table 1 below. The rural roads (R) span most traffic and condition categories. Inter-urban roads (I) are represented on the medium to very highly trafficked roads.

Table 1: Characteristics of the Road Network

Roughness (m/km IRI)	**Surface Age < 6 Years**				**Surface Age 6-12 years**				**Surface Age > 12 Years**			
	Traffic Volume[1]											
	L	**M**	**H**	**VH**	**L**	**M**	**H**	**VH**	**L**	**M**	**H**	**VH**
Good (IRI<1.5)	R	R	I/R	I/R	R	I/R	I/R	I/R	R	I/R	I/R	I/R
Fair (1.5≤IRI<2.0)	-	R	R	I/R	R	I/R	R	I/R	R	I/R	I/R	I/R
Poor (IRI≥2.0)	R	R	-	R	R	R	-	I/R	R	R	I/R	I/R

Note: [1] Traffic volume, L < 1500 AADT, M = 1500-6000 AADT, H = 6000-8000 AADT, VH > 8000 AADT

All pavement sections are located within the same climatic region with consistent sub-soil conditions. Each section has a defined length, width, number of lanes, AADT, soil type, year of construction, base thickness, base material type, most recent treatment, and surface thickness. In addition, surface condition assessments (International Roughness Index, IRI, and others), extent of distresses, and predicted trigger or needs year are specified for all sections.[1] A sample of the information contained within the pavement network spreadsheet is shown in Appendix A.

Structures Network

The structures network file contains three structure types: bridges, culverts, and signs. All structures within the network are situated on the roadways contained within the pavement network. Each structure is referenced to the pavement section in which it is situated.

The bridge component is comprised of 161 bridges. Bridges are one of two basic types, standard bridges which are built according to standard drawings (plans) and major bridges which do not fit the standard bridge plans (due to length, height, or site conditions). Each bridge has a defined bridge length, number of spans, maximum span length, span type, clear roadway width, skew angle, usage, first year in service, and load capacity. In addition, a condition rating, sufficiency rating, and replacement cost is specified for each bridge. A sample of the information contained within the bridge network spreadsheet is shown in Appendix B. Also provided in Appendix B is a table of expected service life for each bridge subtype.

The culvert component of the structures network is comprised of 356 culverts. Each culvert has a maximum diameter, span type, clear roadway width, skew angle, and first year in service. As with bridges, the replacement cost, condition rating, and sufficiency rating of each culvert is specified. A sample of the information contained within the pavement network spreadsheet is shown in Appendix C. Also provided in Appendix C is a table of expected service life for each type of culvert.

[1] These needs years are based on internal section specific performance models which are automatically recalibrated with each annual data upload. For performance prediction after preventive maintenance, rehabilitation, or reconstruction is carried out, straight line performance prediction (e.g. IRI progression) is provided in Appendices, as subsequently described.

The sign component of the structures network is comprised of 45 major signs. Each sign has a defined type and first year in service, as well as a condition rating. A sample of the information contained within the sign network spreadsheet is shown in Appendix D. Also provided in Appendix D is an explanation of expected service life for signs.

Treatments, Service Lives, Unit Costs, and Other Analysis Features

All treatments selected for the pavements and structures should be based on customary practices for the region. To facilitate this, a pavement rehabilitation and preventive maintenance treatment list and selection guideline is provided in Appendix E. Included is a decision tree that incorporates all customary treatment alternatives. The applicability of each alternative, as well as the associated unit cost, expected service life, and expected effect are identified. Also included are the following:

- Reduction in IRI, if any, for each treatment implementation (e.g. relationship between IRI before and after treatment);
- Annual rate of increase of IRI for each treatment-road type combination.

The available treatments, service lives, unit costs, etc. for all bridge, culvert, and sign assets contained within the network are also provided as part of the Challenge, as noted above.

Five vehicle types are defined for the network, as follows:

- Passenger Vehicles
- Recreation Vehicles
- Buses
- Single Unit Trucks
- Tractor Trailer Combinations

Percentage of the AADT volume for each type is outlined in the Appendix F. Since buses generally represent a very small percentage of the total, they might be combined with the tractor trailer combinations as an approximation for vehicle operating cost calculations. As well, recreation vehicles and single unit trucks may be combined.

Increase in vehicle operating costs due to increase in pavement roughness, represented by IRI, is also provided in Appendix F.

The discount rate for investment analysis is specified as 6%. However, challenge respondents may wish to also explore the sensitivity of their analysis to higher and/or lower rates.

The Challenge Issues

The analysis to be performed for an analysis period of 20 years will include the following:

- The budget required to preserve the existing service level for the entire network;
- The effect on service level should the budget be 10% less than or 10% more than that required to preserve the existing service level;
- The incorporation of Vehicle Operating Costs (VOC) in the analysis.

Investments should be broken down into preventive and rehabilitative maintenance and replacement/ reconstruction, which are part of the road authority's capital budgeting. Routine maintenance is carried out in five year term maintenance contracts and is not considered by this capital investment Challenge.[2]

Since the interurban part of the network has higher traffic volumes than the rural part, recommendations about a strategic balance of investment will be a part of the Challenge.

A set of policy objectives, as defined by the road authority, are provided in Appendix G. Accordingly, another key part of the Challenge will be to "translate" these into quantifiable

[2] These contracts are base on schedules of rates and include activities ranging from crack sealing and pothole repairs, to maintenance of signs to litter control to accident response and cleanup to snow and ice control in the winter.

parameters such as Key Performance Indicators (KPI's), level of service indices or…………., in communicating the results and recommendations from the analysis.

For those interested in utilizing the HDM4 package, the reset/ calibration factors applicable to the network are provided in Appendix G.

The Solution(s)/ Outcomes

The results of the analysis should be presented in a format suitable for an informed manager. As well, an abbreviated or summarized version understandable to other interested individuals, organizations, or the public at large should be included. This may require further "translation" of the quantified KPI's into such levels of service indicators as A to F, for example.

Submissions should address the issue of low volume network investment versus high volume network investment (eg., the strategic balance previously noted).

The outcomes should include a documentation of any assumptions needed to carry out the analysis as well as an explanation of the analysis methodology. Any additional data or refinements to improve the clarity or transparency of the outcomes should be clearly defined.

Classification of the system or analysis procedures used in relation to the investment decision framework (after Robertson 2002) in Table 2 should be identified.

Table 2: Classification of Decision Support Levels for Road Asset Management Systems

Decision Support Level	Dominant Characteristic
1	Basic asset data, rule-based work allocation
2	Project and network level assessment, geographic reference
3	Live cycle cost analysis of agency impacts
4	Life cycle cost analysis of agency and user impacts, economic prioritization
5	Optimum investments within constraints, sensitivity analysis
6	Economic, social, environmental multi-criteria assessment, risk analysis

Basic Rules/ Procedures

The ‘Challenge’ will be performed within the following framework of basic rules/ procedures:

- It will not aim to select a ‘winner’ or group of ‘winners’; rather, the aim is to identify and disseminate ‘good practice’.
- The ‘Challenge’ should not be construed as merely providing an opportunity to demonstrate an existing pavement or road asset system, but will require respondents to present an innovative, structured response to a stated problem.
- The ‘Challenge’ responses should be presented and structured as a submission to an informed manager as a real-life case. Also, a summary should be presented as information for other interested organizations or the public at large.

Timetable

January 2007	Issuance of Call for Expressions of Interest, posted on ICMPA7 website and publicized elsewhere in various forms.
April 2007	Deadline for Receipt of Responses
July 2007	Issuance of Invitations, Accompanied by Terms of Reference
December 2007	Draft Submissions for the Challenge and Beginning of Reviews by Panel
February 2008	Feedback from Panel
April 2008	Final Submissions and Preparation for Poster Sessions
June 2008	Conference

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Ralph Haas, Challenge Chair

Appendix A - Pavement Network Information

Table A.1 contains a sample of the information provided in the pavement network spreadsheet. The spreadsheet fields are as follows:

General	
Hwy ID	Highway number and section identifier
Hwy Dir	Highway direction of travel: R - Increasing chainage (north, east) L - Decreasing chainage (south, west) C - Both directions
Hwy Type	Highway Type: I - Interurban R - Rural
From (km)	Chainage of subsection start point
To (km)	Chainage of subsection end point
Width (m)	Width of pavement (includes paved shoulders)
Soil Type	Refer to Table A.2 (based on the Unified system)
Pavement	
Base - Type	Base material type (refer to Table A.3)
Base - Year	Year of base construction
Base - mm	Base thickness
Last Activity - Type	Most recent, non routine treatment (refer to Table A.4)
Last Activity -Year	Year of most recent, non routine treatment
Surf (mm)	Surface thickness
Seal Coat	Year of most recent seal coat
Traffic	
AADT	Average Annual Daily Traffic (two-way)
ESAL/Day	Equivalent Single Axle Loads per day (per direction)
Condition[3]	
PQI	Pavement Quality Index (/10)[4]
IRI	International Roughness Index (m/km)
SDI	Surface Distress Index (/10)
SAI	Structural Adequacy Index (/10)
Distress	
TRc %Ar	Transverse cracking (percentage area)
LWPc %Le	Longitudinal wheel path cracking (percentage length)
OtherC %Ar	Other cracking (percentage area)
RUT (mm)	80^{th} percentile rut depth (i.e. 80% are less than the value)
Predicted	
Need Year	Predicted rehabilitation need or trigger year
Index Type	Performance index predicting rehabilitation need year

[3] See the Transportation Association of Canada "Pavement Design and Management Guide", 1997 for a detailed description of these indices

[4] PQI is a composite measure of ride, surface distress, and structural adequacy

Table A.1 Sample Spreadsheet for Pavement Network

							PAVEMENT							TRAFFIC		CONDITION				DISTRESS				PREDICTED	
Hwy ID	Hwy Dir	Hwy Type	From (km)	To (km)	Width (m)	Soil Type	Base Type	Base Year	Base mm	Last Activity Type	Last Activity Year	Surf (mm)	Seal Coat	AADT	ESAL /Day	PQI	IRI	SDI	SAI	TRc %Ar	LWPc %Le	OtherC %Ar	RUT (mm)	Need Year	Index Type
3A	C	R	0.0	4.4	12.6	CL	ACB	1976		OL	1991	280	1995	10700	688	7.5	1.6	8.7	5	0	0	0	5	2014	PQI
3A	C	R	4.43	5.45	12.6	CL	ACB	1976		OL	2003	380		10700	688	7.4	1.3			0	0	0	5	2013	PQI
3A	C	R	5.5	6.5	12.6	CL	ACB	1976		OL	1991	280	1995	10700	688	6.3	2		5.3	0	0	0	5	2009	PQI
3A	C	R	7.1	7.3	12.4	CL	ACB	1973		OL	2006	380	2007	10700	688	6.2	2			0	0	0	4	2009	PQI
3A	C	R	8.0	8.4	9.8	CL	ACB	1973		OL	1991	330	1995	10700	688	5	2.8		5.1	0	0	0	3	2009	PQI
3A	L	R	4.5	5.2	6.6	CL	ACB	1976		OL	2003	380		10700	688	6.5	1.9			0	0	0	2	2009	PQI
3A	L	R	6.5	7.1	6.6	CL	ACB	1976		OL	2006	330		10700	688	6.4	1.9		9	0	0	0		2009	PQI
3A	R	R	4.5	5.2	6.6	CL	ACB	1976		OL	2003	380		10700	688	7	1.5			0	0	0	7	2011	PQI
3A	R	R	6.5	7.1	6.6	CL	ACB	1976		OL	2006	330		10700	688	5.1	2.8			0	0	0	4	2009	PQI
72C	L	I	0.0	0.4	11.6	CL	GBC	1959	180	OL	2006	286	2008	13300	1328	7.9	1.5	10		0	0	0	4	2012	IRI
72C	L	I	0.4	0.8	11.6	CL	GBC	1959	180	OL	2006	386	2008	13300	1328	8.3	1.1	10		0	0	0	3	2016	IRI
72C	L	I	0.8	1.2	11.6	UK	GBC	1959	175	OL	2006	301	2008	13300	1328	8.3	1.2	10		0	0	0	4	2016	IRI
72C	L	I	1.2	1.5	11.6	UK	GBC	1959	175	OL	2006	301	2008	13300	1328	8.3	1.2	10		0	0	0	4	2016	IRI
72C	L	I	1.5	3.0	11.6	CL	ACB	1978		OL	2006	376	2008	13300	1328	8.2	1.3	10		0	0	0	4	2015	IRI
72C	L	I	3.0	5.5	11.6	CL	GBC	1959	180	OL	2006	306	2008	13300	1328	8.3	1.2	10		0	0	0	4	2015	IRI
72C	L	I	5.5	7.7	12	CL	GBC	1959	180	OL	2006	290	2008	13300	1328	8.1	1.3	10		0	0	0	5	2014	IRI
72C	L	I	7.7	15.1	12	CL	GBC	1959	180	OL	2006	306	2008	13257	1305	8	1.4	10		0	0	0	4	2013	IRI
72C	R	I	0.0	0.4	11.6	CL	ACB	1975		OL	2006	362	2008	13300	1328	8.3	1.2	10		0	0	0	4	2014	IRI
72C	R	I	0.4	7.9	11.6	CL	ACB	1978		OL	2006	382	2008	13300	1328	8.2	1.3	10		0	0	0	3	2014	IRI
72C	R	I	7.9	15.0	12	CL	ACB	1978		OL	2006	360	2008	13256	1305	8.2	1.3	10		0	0	0	4	2014	IRI
132C	C	R	0.0	0.7	11.8	CI	CSB	1987	180	ACP	1987	150	1995	3320	343	7.1	2	9.2	9.3	0	0	0	5	2011	IRI
132C	C	R	0.7	5.1	11.8	CI	CSB	1987	180	HIR	2003	150		2947	354	8.2	1.2	9.7		0	0	0.2	4	2022	SDI
132C	C	R	5.1	13.9	12	CI	CSB	1988	180	HIR	2003	130		2400	366	8	1.3	9.7		0	0	0.2	4	2022	PQI
132C	C	R	13.9	14.4	12	CI	CSB	1964	125	OL	1988	190	1995	2230	322	6.9	1.9	7.9	9.6	2.1	0	0.4	4	2013	PQI
132C	C	R	14.4	15.0	12	CI	CSB	1988	180	ACP	1988	130	1995	2230	322	7.1	1.7	7.9	9.5	2.1	0	0.4	5	2013	SDI
132C	C	R	15.0	15.4	12	CI	CSB	1964	125	OL	1988	190	1995	2230	322	7.1	1.7	7.9	9.4	2.1	0	0.4	4	2014	PQI
132C	C	R	15.4	15.7	12	CI	CSB	1988	180	ACP	1988	130	1995	2230	322	6.5	2.3	7.9	6.4	2.1	0	0.4	6	2009	IRI
132C	C	R	15.7	17.0	12	CI	CSB	1988	180	ACP	1988	130	1995	2230	322	6.4	2.4	7.9	9.7	2.1	0	0.4	5	2009	IRI
132C	C	R	17.0	19.5	12	CI	CSB	1964	125	OL	1988	180	1995	2230	322	6.4	2.3	7.9	8.3	2.1	0	0.4	6	2009	IRI
132C	C	R	19.5	19.8	12	CI	CSB	1965	125	OL	1991	180	1995	2230	322	6.7	2.1	7.9	6.8	2.1	0	0.4	4	2010	IRI
132C	C	R	19.8	22.5	12	CI	GBC	1991	250	ACP	1991	115	1995	2230	322	6.8	2.2	8.7	7.3	0	0	0	6	2009	IRI
132C	C	R	22.5	23.1	12	CI	CSB	1965	125	OL	1991	180	1995	2230	322	7.1	1.9	8.7	9.7	0	0	0	4	2012	IRI

Table A.2 Soil Type Classifications

Code	Classification
CH	Organic clays of high plasticity
CI	Clays of medium plasticity, gravelly clays, sandy clays, silty clays
CL	Inorganic clays of low plasticity, gravelly clays, sandy clays, silty clays, lean clays
GC	Clayey gravels, gravel-sand-clay mixtures
GM	Silty gravels, gravel-sand-silt mixtures
GP	Poorly graded gravels
OL	Organic silts and organic silty clays of low plasticity
SC	Clayey sands, sand-clay mixtures
SM	Silty sands, sand-silt mixtures
UK	Unknown soil types
SP	Poorly graded sands, little or no fines

Table A.3 Base Type Classifications

Code	Classification
ACB	ACBC - Asphalt Concrete Base Course
COM	Composite Pavement (ACP[5] over PCC[6])
CSB	CSBC - Cement Stabilized Base Course
GBC	Granular Base Course

Table A.4 Last Activity Treatments

Code	Treatment Type
AC	AC[7]
ACP	Base & non-stage ACP
ACP1	Base & 1st stage paving
ACP2	2ND stage AC paving (final paving)
CM&OL	Cold mill & overlay
CMIn	Cold mill & inlay
CMIn&OL	Cold mill inlay & overlay
HIR	Hot-in-place recycle
OL	AC overlay

[5] ACP (Asphalt Concrete pavement) can include binder and surface course layers
[6] PCC (Portland Cement Concrete) would generally be plain, jointed
[7] AC (Asphalt Concrete), as a general term

Appendix B - Bridge Network Information

Table B.1 contains a sample of the information provided in the bridge network spreadsheet. The spreadsheet fields are as follows:

Structure ID	Bridge identifier
Bridge Cat	Bridge category: STD - Standard bridge MAJ - Major bridge
Hwy ID	Number and section identifier of highway that goes over bridge
Hwy Dir	Highway direction of travel which bridge services: R - Increasing chainage (north, east) L - Decreasing chainage (south, west) C - Both directions
KM	Chainage of bridge from start of pavement section
Usage Code	Refer to Table B.2
Replacement Cost ($)	??????????????????????(or initial construction cost)[8]
First Year In Service	First year current structure brought into service
Unique Span Type	Refer to Table B.3
Max Span Ln (m)	Length of longest span
No of Spans	Number of spans
Nominal Bridge Ln (m)	Combined length of all spans
Total Clear Roadway (m)	Minimum curb to curb distance
Cond Rat	Condition rating (/100)
Insp Date	Date of condition inspection

Table B.4 contains expected service life for each type of bridge.

[8] This does not include user delay costs during replacement construction

Table B.1 Sample Spreadsheet for Bridge Network

Structure ID	Bridge Cat	Hwy ID	Hwy Dir	KM	Usage Code	Replacement Cost ($)	First Year In Service	Unique Span Type	Max Span Ln (m)	No of Spans	Nominal Bridge Ln (m)	Total Clear Roadway (m)	Cond Rat	Insp Date
B1	STD	135A	C	14.818	RV	89000	1978	VS	6.1	1	6.1	13.7	55	20-8-2006
B2	MAJ	231B	C	23.774	RV	3426000	1977	VF	36.6	4	146.4	8.5	61	8-1-2008
B3	MAJ	150A	C	21.298	RV	1093000	1958	PJ	18.9	3	45.7	8.5	50	18-11-2006
B4	MAJ	135F	C	41.787		624000	1996	SCC	12	3	30	9.2	72	19-8-2006
B5	MAJ	132B	C	11.901	RO	1284000	1962	CT	23.8	3	58	11.6	44	12-5-2007
B6	MAJ	150B	C	27.285	RV	682000	1964	SCC	12	3	32.8	11	72	19-5-2007
B7	MAJ	6A	C	2.83		1240000	1967	RB	26.5	2	53.3	8.5	55	11-11-2006
B8	MAJ	75A	R	1.113		3635000	1973	FC	33.5	4	134	12.2	50	29-3-2007
B9	MAJ	75A	L	1.116	RV	3714000	1996	DBC	36	4	134	12.5	72	29-3-2007
B10	MAJ	9A	C	1.476		3936000	1960	CT	37.8	5	168.2	9.1	50	16-6-2007
B140	MAJ	285A	C	0	GS	1670000	1980	LF	38.1	2	76.2	12.2	55	11-3-2007
B141	MAJ	75D	L	24.347	GS	1428000	1982	WG	39	2	78	9.1	66	11-3-2007
B142	MAJ	75D	L	7.847	PS	1860000	1980	PQ	36.9	4	129.2	2.1	55	30-3-2007
B143	MAJ	135H	C	0.756	RV	889000	1985	DBT	38	1	38	10.7	55	19-8-2006
B144	MAJ	135C	C	28.115		1092000	1987	DBT	42	1	42	9.5	66	21-8-2006
B145	MAJ	9A	L	5.452	RO,GS	3710000	1985	WG	32	4	106	16	66	16-6-2007
B146	MAJ	75F	L	24.538	GS		2007	WG	35	3	94	11.8		
B147	MAJ	135H	C	14.531	RV	1248000	1988	WG	22	3	60	11	50	20-9-2007
B148	STD	102B	C	25.162	RV	257000	1987	SM	11	1	11	13.7	50	1-12-2006
B149	MAJ	75G	L	22.274	GS	3279000	1998	WG	37	3	94	16	88	4-7-2006
B150	STD	72C	R	25.035		244000	1984	SM	11	1	11	13.7	50	1-9-2007
B151	MAJ	66B	C	22.354	IC	747000	1987	SMC	10	3	30	13.2	77	14-1-2007
B152	MAJ	141A	C	38.05		1109000	1985	WG	22	2	44	13.5	44	14-1-2007
B153	STD	132B	C	7.802	SP	68000	1961	TP	1.9	1	1.9	11	55	12-5-2007
B154	MAJ	78B	R	28.364		6290000	1999	WG	66	3	170	12.4	88	16-6-2007
B155	MAJ	78B	L	28.012		6290000	1999	WG	66	3	170	12.4	94	16-6-2007
B156	MAJ	78B	L	31.073	GS	5160000	1999	WG	60	3	135	12.4	77	23-6-2007
B157	MAJ	78B	R	0.012	GS	2070000	1996	WG	34	2	68	16.1	88	29-3-2007

Table B.2 Bridge Usage Categories

Code	Description of Usage
GS	Grade Separation (Railway Not Involved)
IC	Irrigation Canal Crossing
PS	Pedestrian Grade Separation
RO	Railway Overpass (Road Goes Over Railway)
RU	Railway Underpass (Road Goes Under Railway)
RV	River or Stream Crossing
SP	Stockpass or Cattlepass

Table B.3 Bridge Span Types

STANDARD BRIDGES			
Category		**Code**	**Type**
Timber		TP	Timber-Pile or Timber-Box
		TT	Treated-Beam
Prestressed		SCC	(SMC) for CS750
		SM	Metric (VS)
		SMC	SM Composite
		VS	Type VS
		VSO	Type VS Overlaid
Precast		HC	HC Stringer
MAJOR BRIDGES			
Category		**Code**	**Type**
CONCRETE	Prestressed Girder	CBC	(CBT) for CS750
		DBC	(DBT) for CS750
		CBT	Composite Bulb-T
		DBT	Decked Bulb-T
		FC	Type-FC
		FM	Metric (LF)
		LF	Latest Fenrich
		PJ	Other
		PM	Type-M
		PO	Type-O
		PQ	Tee Girder
		RD	Type-RD
		RM	Metric (RD)
		VF	(FC) for HS25
	Precast Girder	PE	E Stringer
	Cast-In Place	CA	Concrete-Arch
		CF	Concrete-Frame
		CS	Flat Slab
		CT	Concrete-Tee
		CV	Voided-Slab
		CX	Box
STEEL	Beam	FR	Rigid Frame
		WG	Welded Girder
		RB	Rolled Beams
		RG	Riveted Plate Girder
	Truss	TH	Through Truss

Table B.4 Expected Service Life for Bridges

STANDARD BRIDGES			
TYPE	LIFE EXPECTANCY (YEARS)		
	Low	Average	High
Treated Timber (TP, TT)	35	40	45
Prestressed - Composite (SCC, SMC)	55	60	70
Prestressed (SM, VS)	40	45	60
Prestressed Overlaid (VSO)	45	50	65
Precast (HC)	30	35	50
Considerations in Determining Life Expectancy: • traffic characteristics – volume, amount of truck traffic • salt usage – road surfacing, traffic, climatic conditions • deck drainage, leakage			

MAJOR BRIDGES				
TYPE		LIFE EXPECTANCY (YEARS)		
		Low	Average	High
CONCRETE	Prestressed Girder (CBC, DBC, CBT, DBT, FC, FM, LF, PM, PO, PQ, PJ, RD, RM, VF)	45	55	70
	Precast Girder (PE)	30	35	50
	Cast-in place (CA, CF, CS, CT, CV, CX)	40	50	60
STEEL	Rigid Frame (FR) & Welded Girder (WG)	60	70	80
	Rolled Beams (RB)	50	60	80
	Riveted Plate Girder (RG)	40	50	70
	Through Truss (TH)	40	50	70
Considerations in Determining Life Expectancy: • traffic characteristics – volume, amount of truck traffic • salt usage – road surfacing, traffic, climatic conditions • deck drainage, leakage • design or rated load capacity				

Appendix C - Culvert Network Information

Table C.1 contains a sample of the information provided in the culvert network spreadsheet. The spreadsheet fields are as follows:

Structure ID	Culvert identifier
Hwy ID	Number and section identifier of highway that goes over culvert
Hwy Dir	Highway direction of travel which culvert services: R - Increasing chainage (north, east) L - Decreasing chainage (south, west) C - Both directions
KM	Chainage of culvert from start of pavement section
Replacement Cost ($)	??????????????????????(or initial construction cost)[9]
First Year In Service	First year current structure brought into service
Unique Span Type	Refer to Table C.2
Max Pip Dia (mm)	Maximum Diameter of Culvert
Total Clear Roadway (m)	Width of highway over culvert (shoulder edge to shoulder edge)
Cond Rat	Condition rating (/100)
Insp Date	Date of condition inspection

Table C.2 also contains expected service life for each type of culvert.

[9] This does not include user delay costs during replacement construction

Table C.1 Sample Spreadsheet for Culvert Network

Structure ID	Hwy ID	Hwy Dir	KM	Replacement Cost ($)	First Year In Service	Unique Span Type	Max Pipe Dia (mm)	Total Clear Roadway (m)	Cond Rat	Insp Date
C1	75A	L	9.159	72000	1995	MP	2400	12.4	88	21-4-2007
C2	237D	C	36.006	33000	1957	MP	1500	7.4	55	29-11-2007
C3	6A	C	7.15	173000	1992	RPA	10462	13.4	77	11-11-2006
C4	6A	C	14.727	120000	1992	SP	2438	13.8	77	11-11-2006
C5	102D	C	1.34	219000	1991	SP	4920	13.1	77	30-11-2006
C6	72D	L	15.571	363000	1982	RPE	6500	24.8	44	8-9-2007
C7	90A	C	13.751	346000	1991	SP	3962	12.7	55	9-3-2007
C8	150B	C	5.641	123000	1965	SPE	2603	11.1	77	17-11-2006
C9	135E	C	10.6	929000	1996	RPB	6462	11	77.8	4-3-2008
C10	102D	C	33.45	829000	2002	SP	4300	14.6	88	30-11-2006
C11	78B	L	18.907	168000	1998	MP	2400	34.8	88	20-7-2007
C12	93A	C	4.51	370000	1983	RPE	4929	13	44	11-7-2006
C13	90A	C	8.306	234000	1991	SP	3962	12.7	88	9-3-2007
C14	135A	C	2.09	171000	1959	SPE	2605	11.7	33	7-10-2006
C15	150A	C	15.915	157000	1980	MP	1829	11.8	77	17-11-2006
C16	150B	C	10.211	125000	1963	SPE	2905	11.4	66	17-11-2006
C17	135E	C	35.446	75000	1991	SP	2134	13.7	88.9	22-3-2008
C18	135F	C	43.888	79000	1964	SPE	1738	9.2	88.9	28-2-2008
C19	150B	C	42.437	837000	1976	BP	4300	10.6	77	19-5-2007
C20	132C	C	11.265	141000	2004	RPA	9480	12.1	100	11-5-2007
C21	72D	L	23.224	97000	1987	SP	1828	26	100	24-8-2007
C22	72D	L	36.027	115000	1982	RPP	2620	25.7	55	24-8-2007
C23	231B	C	16.148	61000	1954	MP	1500	8.1	55	8-1-2008
C24	195A	C	9.885		1960	MP	1200	10.8		
C25	195A	C	15.398	95000	1959	MP	1200	8.5	33	9-1-2008
C26	135D	C	20.874	162000	1952	SPE,BP	1800	11.7	44.4	3-3-2008
C27	72C	L	12.818	547000	1958	RPP,AP	5480	25.3	55	31-8-2007
C28	138B	C	0	68000	1991	MP	2200	13	77	23-1-2007

Table C.2 Culvert Span Types and Expected Service Life

CODE	TYPE	LIFE EXPECTANCY (YEARS)		
		Low	**Average**	**High**
AP	CIP Arch	40	50	60
BP	CIP Box, Cell	40	50	60
BPR	Cast in place Box Culvert	50	60	70
CP	Precast-Pipe	50	60	70
CPA	Precast Arch Culvert	50	60	70
FP	CSP or CMP Arch	40	50	60
MP	CSP or CMP Ellipsed	40	50	60
MPB	CSP Integral w/Bridge	40	50	60
MPE	CSP or CMP Ellipsed	40	50	60
PCB	Precast Box, Cell	50	60	70
RPA	SPCSP Arch Beams (ABC)	50	60	70
RPB	SPCSP Integral w/Bridge	50	60	70
RPE	SPCSP Ellipse	50	60	70
RPP	SPCSP Arch Pipe	50	60	70
SCA	Structural Culvert-Arch(Super Cor)	60	70	80
SP	SPCSP or SPCMP Round	50	60	70
SPE	SPCSP or SPCMP Ellipsed	50	60	70
TP	Timber-Pile or Timber-Box	40	50	60
WP	Wood-Stave	40	50	60

Notes:

1. Life expectancies in the table are speculative since a long term record of replacements due to various factors is not available.
2. Culvert replacements would generally be due to structural failure, washouts, and/or road construction than due to reaching an end of service life.
3. Good maintenance could well prolong life expectancies beyond the numbers in the table.

Appendix D – Major Sign Network Information

Table D.1 contains a sample of the information provided in the major sign network spreadsheet. The spreadsheet fields are as follows:

Structure ID	Sign identifier
Sign Type	Truss, Tube, or Cantilever
Hwy ID	Number and section identifier of highway sign located on
Hwy Dir	Highway direction of travel which sign services: R - Increasing chainage (north, east) L - Decreasing chainage (south, west) C - Both directions
KM	Chainage of sign from start of pavement section
First Year In Service	First year current structure brought into service
Cond Rat	Condition rating (/100)
Insp Date	Date of condition inspection

Notes:

1. Expected service lives for these signs are not provided since, for safety and other reasons, periodic inspection and regular maintenance is directed to keeping the signs clean and in good repair well into the future. Any replacements would likely be incurred by road reconstruction or catastrophic damage due to a storm or accident.
2. Replacement costs, in accordance with 1, are also not provided. However, for any investment analysis which wishes to consider asset value of the infrastructure, an approximate written down replacement cost for each sign structure could be assumed at $100,000.

Table D.1 Sample Spreadsheet for Sign Network

Structure ID	Sign Type	Hwy ID	Hwy Dir	KM	First Year In Service	Cond Rat	Insp Date
S1	Truss	138C	L	0.952	1971	72	10-3-2007
S2	Truss	138C	L	0.114	1971	77	10-3-2007
S3	Truss	138C	L	0.114	1971	66	10-3-2007
S4	Truss	138C	L	0.114	1971	77	10-3-2007
S5	Truss	75G	R	24.71	1998	94	4-7-2006
S6	Truss	75G	R	36.068	1964	50	10-7-2006
S7	Truss	75G	R	36.068	1964	72	10-7-2006
S8	Truss	102B	R	34.744	1966	72	10-7-2006
S9	Truss	102B	R	34.744	1966	66	10-7-2006
S10	Truss	135E	L	0.167	1969	66	13-9-2007
S21	Tube	6B	R	0.008	2006	100	8-4-2007
S22	Cantilever	6B	R	0.423	2006	100	8-4-2007
S23	Tube	6B	R	0.515	2006	72	8-4-2007
S24	Tube	6B	R	0.008	2006	100	8-4-2007
S25	Tube	6B	R	0.008	2006	100	8-4-2007
S26	Tube	6B	R	0.008	2006	100	8-4-2007
S27	Truss	75F	L	16.521	1978	77	15-5-2006
S28	Truss	72B	R	8.099	1973	77	1-9-2007
S29	Truss	9A	R	4.963	1987	66	16-6-2007
S30	Truss	9A	R	4.963	1987	66	23-6-2007
S31	Truss	9A	R	4.963	1987	83	23-6-2007
S32	Truss	78A	L	43.839	1997	100	29-3-2007
S33	Tube	6C	R	0.311	2006	100	12-4-2007
S34	Tube	6C	R	0.311	2006	100	12-4-2007
S35	Truss	75D	R	4.963	2001	100	11-3-2007
S36	Tube	96C	L	0.098	1993		
S37	Tube	96B	R	44.006	1993		
S38	Tube	99A	L	0.119	1993		
S39	Tube	96B	C	42.669	1993		

Appendix E - Pavement Rehabilitation and Preventive Maintenance Treatments

Table E.1 contains a list of possible pavement rehabilitation and preventive maintenance treatments while Figure E.1 contains a decision tree to guide decision making. Figure E.2 contains roughness improvements following treatments while Table E.2 specifies annual rates of increase in IRI following rehabilitation.

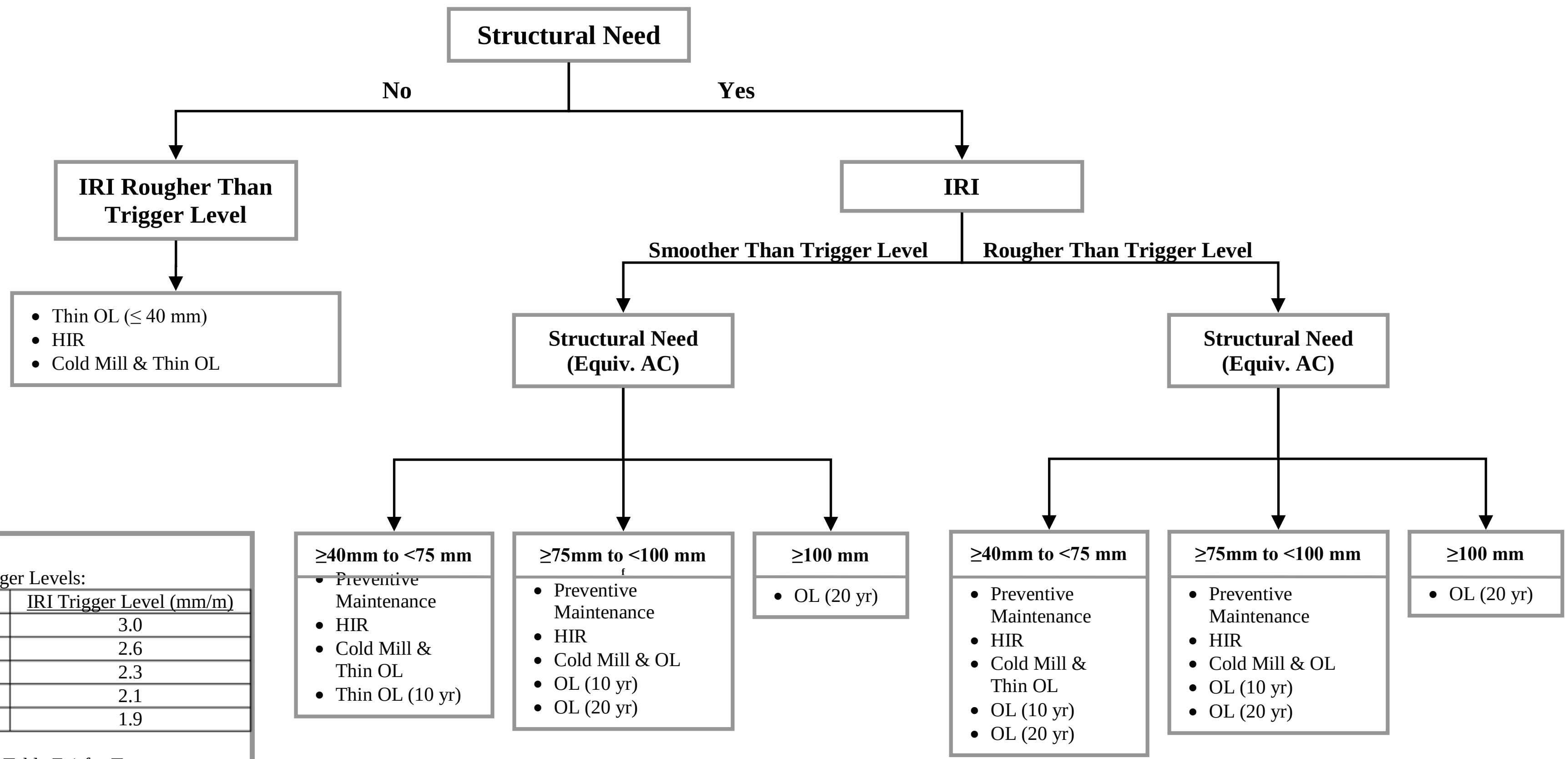
Table E.1: Pavement Rehabilitation and Preventive Maintenance Treatment Alternatives

No.	Treatment	Type[10]	Applicability	Unit Costs[11]	Expected Service Life	Expected Effect	Remarks
1	Thin Overlay (40 mm or less in thickness)	PM	Rough pavements with or without surface deficiencies but structurally adequate; can be applied to structurally inadequate pavements to defer grade widening or reconstruction. Would not generally be considered for high volume roadways	$6.00/m^2$ to $7.50/m^2$	Structurally adequate pavement: ≤ 10 years Structurally inadequate pavement: ≤ 5 years	Reduces IRI	• Can treat travel lanes only or full width • May not be able to meet QA smoothness specifications
2	Reprofiling by Cold Milling and Overlay	SP	Rough pavements with or without surface deficiencies and modest strengthening needs	$9.00/m^2$	≤ 15 years	Reduces IRI and improves general roughness; restores structural integrity	• Overlay based on structural design
3	Cold Mill and Inlay, or HIR of Travel Lanes, plus Overlay	SP	Pavements with severe surface deficiencies and strengthening needs as determined by condition evaluation and/or deflection testing or other means	$15.00/m^2$ to $16.50/m^2$	≤ 15 years	Reduces IRI and improves general roughness; restores structural integrity	• Overlay based on structural design
4	Structural Overlay	SP	Structurally deficient pavements as determined by condition evaluation and/or deflection testing, or other means	$10.50/m^2$ to $16.50/m^2$	10 year design: 10 years 20 year design: 20 years	Reduces IRI and improves general roughness, increases or restores structural integrity	• Structural deficiency can result from under-design or increased traffic loading • Overlay thickness based on structural design

[10] PM is preventive maintenance
SP is strengthening (e.g. structural preservation)
RC is reconstruction

[11] Expected 2008 unit costs

No.	Treatment	Type	Applicability	Unit Costs	Expected Service Life	Expected Effect	Remarks
5	Cold Mill and Inlay	PM	Rough and/or rutting distress but structurally adequate pavements; interim measure to improve ride quality until overlay needed	\$9.00/m²	Structurally adequate pavement: ≤ 10 years Structurally inadequate pavement: < 10 years	Reduces IRI and improves surface condition	• Typically 50 mm cold mill depth • Treatment applied to travel lanes only
6	Hot-In-Place Recycling (HIR)	PM	Rough but structurally adequate pavements; interim measure to improve ride quality until overlay needed	\$7.50/m²	Structurally adequate pavement: ≤ 8 years Structurally inadequate pavement: < 8 years	Reduces IRI and improves surface condition	• Pavements with severe deficiencies (e.g. rutting) may not be suitable candidates • Seal Coats, patching and crack sealer may affect mix quality • Treatment applied to travel lanes only
7	Micro-Surfacing	PM	Structurally sound, relatively smooth pavements which may have some surface distress (e.g. raveling, segregation); can also be used as a rut fill treatment	\$4.50/m² to \$6.00/m²	5 years	Seals surface and may increase surface friction	• May be appropriate for semi-urban applications
8	Chip Seal (Surface Seal; Seal Coat)	PM	Structurally sound, relatively smooth pavements; may have some surface distress (e.g. ravelling)	\$3.75/m²	≤ 7 years	Improved surface friction; extended service life of pavement	• No added structural strength
9	Cold In-Place Recycling	RC	Pavements for which preventive maintenance or rehabilitation is not an option (e.g. excessive roughness and/or structural damage)	≈\$37.50/m²	≤ 20 years	Restores IRI, restores structural integrity	• Need surface wearing course
10	Full Depth Reclamation and Stabilization	RC	Pavements for which preventive maintenance or rehabilitation is not an option (e.g. excessive roughness and/or structural damage)	≈\$37.50/m²	≤ 20 years	Restores IRI, restores structural integrity	• Need surface wearing course
11	Reconstruction	RC	Pavements for which preventive maintenance or rehabilitation is not an option (e.g. excessive roughness and/or structural damage)	≈\$37.50/m²	20 years	Restores IRI, restores structural integrity	• Replaces existing structure



Notes:

1. IRI Trigger Levels:

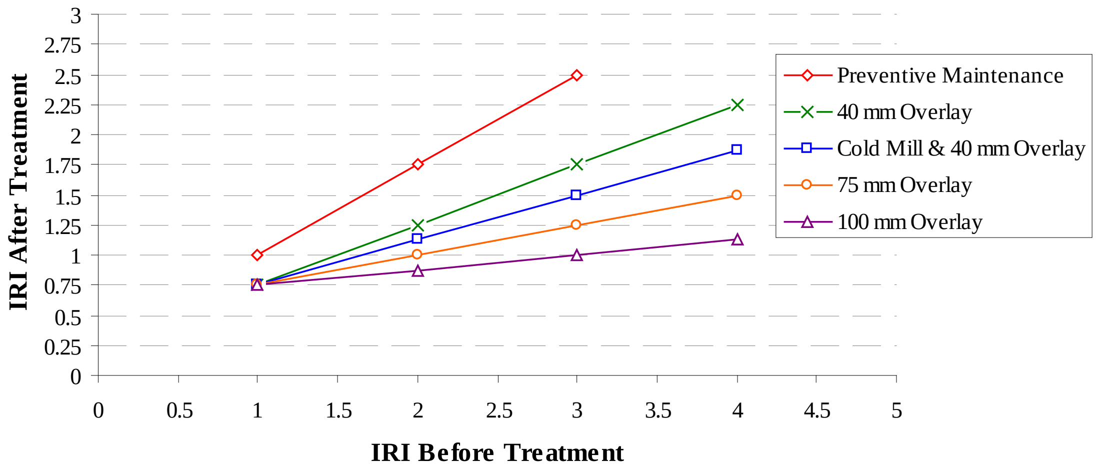
AADT	IRI Trigger Level (mm/m)
< 400	3.0
400-1500	2.6
1500-6000	2.3
6000-8000	2.1
> 8000	1.9

2. Refer to Table E.1 for Treatments

3. Localized roughness, potholes, cracking, rutting, raveling, and segregation distresses are treated in 5-year term routine maintenance contracts with schedules of rates

Figure E.1 Guidelines for Selecting Pavement Rehabilitation and Preventive Maintenance Treatments

Interurban



Rural

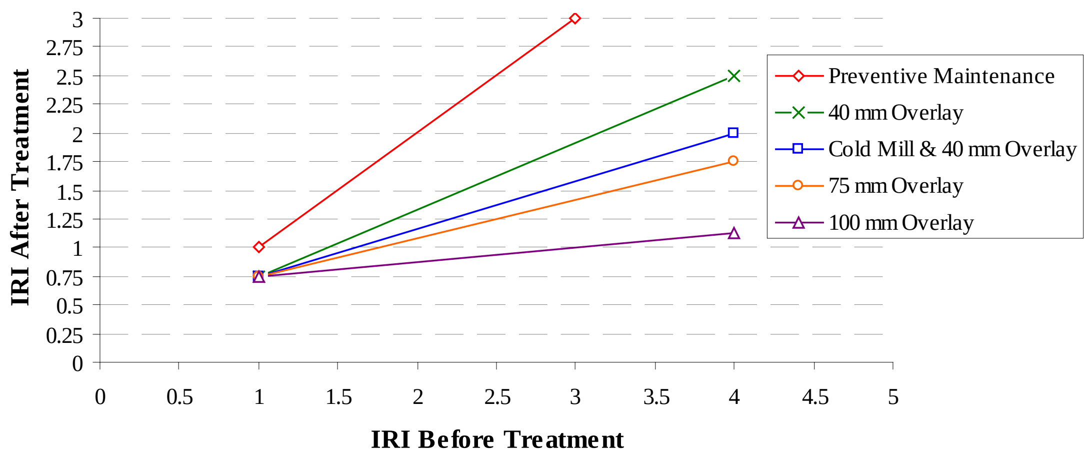


Figure E.2 Roughness Improvement (IRI Before and After) Due to Treatment

Table E.2 Annual Rate of Increase of IRI After Rehabilitation

Road Class	AADT	Rate of Increase in IRI (m/km/yr)
Interurban	> 8000	0.069
	< 8000	0.077
Rural	> 1500	0.091
	< 1500	0.101

Notes:

1. These rates of increase come from a regression analysis of IRI vs. needs year for various road classes. The rates were essentially linear and exhibited quite high R^2 values. Accordingly, it is reasonable to assume that future rates, after a rehabilitation or reconstruction, will generally follow the numbers in Table E.2.
2. Rates of increase for the lower traffic volumes are slightly higher. Again, this is supported by the regression analysis. The likely reason is that lower traffic volume pavements were designed to be less structurally adequate and thus increase in roughness at a slightly higher rate.

Appendix F – Traffic Breakdown and Vehicle Operating Costs

Table F.1 shows the percentage breakdown of the total traffic on each pavement section into traffic classifications. Classification categories include passenger vehicles (PV), recreation vehicles (RV), buses (BU), single unit trucks (SU), and tractor trailer combinations (TT). Figure F.1 shows increased vehicle operating costs as a function of IRI.

Table F.1 Traffic Classification

HWY ID	PV (%)	RV (%)	BU (%)	SU (%)	TT (%)
72A	90	2.4	1.4	2.2	4
72B	88	3.2	0.4	2.8	5.6
72C	84.1	2.9	0.4	3.4	9.2
72D	74.8	4.3	0.5	3.3	17.1
72E	72.7	2.5	0.4	4.2	20.2
3A	90.3	0.6	0.6	4	4.5
75A	73.3	5.5	0.6	3.6	17
75B	75.7	5.2	0.5	3.4	15.2
75C	82.1	3.1	0.5	3.7	10.6
75D	85.6	2.3	0.4	3.3	8.4
75E	80.8	4.6	0.4	3.1	11.1
75F	80.5	2.6	0.5	3.7	12.7
75G	83.1	2.4	0.4	3.9	10.2
6A	87.9	1.8	0.8	5.2	4.3
6B	94.6	1.4	0.5	2.4	1.1
6C	92	1.8	0.4	2.8	3
6D	84.2	2.2	0.5	6.5	6.6
6E	87.5	1.9	0.4	4.2	6
6F	89.9	2.1	0.7	3.8	3.5
6G	93.3	1.1	0.4	3.1	2.1
78A	78.2	6.4	0.8	3.9	10.7
78B	80.9	3.3	0.7	4.1	11
78C	85.5	1.1	0.4	4.8	8.2
9A	78.7	3.7	0.5	4.5	12.6
90A	84.1	4.1	1.4	5.6	4.8
93A	82.9	1.9	0.6	4.7	9.9
96A	74.1	3.9	0.8	7	14.2
96B	85.9	5.4	0.4	3.6	4.7
96C	84.7	5	0.4	5	4.9
96D	81.4	5.7	0.3	3.8	8.8
99A	82.8	5.7	0.8	4.8	5.9
102A	80.6	5.9	0.5	6.2	6.8
102B	89.7	2.7	0.3	3.8	3.5
102C	90.2	2.6	0.2	4	3
102D	83.8	3	0.2	7.3	5.7
105A	80.8	4.6	0.5	6.3	7.8
132A	70.5	6	0.4	5.8	17.3
132B	74.8	6	0.4	6	12.8

HWY ID	PV (%)	RV (%)	BU (%)	SU (%)	TT (%)
132C	77.7	5.4	0.3	6.1	10.5
132D	73.4	8.1	0.3	5.2	13
135A	76.8	7.3	1.1	2.9	11.9
135B	80.3	7	0.3	2.3	10.1
135C	83.4	8.4	0.4	2.7	5.1
135D	87.5	4	0.8	4.2	3.5
135E	84.4	4.7	0.7	4.3	5.9
135F	84.8	3.7	1.1	4	6.4
135G	79.5	5.2	0.4	5.6	9.3
135H	72.1	6.6	0.1	6.8	14.4
135I	76.9	7.3	0.5	5.9	9.4
66A	89.2	3.3	1.1	3.2	3.2
66B	68.5	2.4	0.5	6.7	21.9
138A	76.5	2.5	0.4	4.3	16.3
138B	73.5	4.3	0.9	5.3	16
138C	76.8	4.1	1	5.7	12.4
141A	67.2	5.5	0.4	5.6	21.3
141B	75.2	4	0.4	5.7	14.7
144A	85	1	0.6	6.2	7.2
150A	84.2	3.7	0.4	4.4	7.3
150B	75.3	6.7	0.5	6.1	11.4
150C	77	7.4	0.2	5	10.4
177A	72	1.9	0.5	8.5	17.1
177B	61.6	3.2	0.2	7.1	27.9
177C	63.4	6.1	0.1	7.6	22.8
177D	59.9	7.4	0.2	7	25.5
177E	61.6	6.7	0.4	6.2	25.1
195A	79	4.8	0.3	6.8	9.1
231A	80	5.8	0.7	6.7	6.8
231B	88	3.7	0.2	4.3	3.8
237A	68.6	8.2	1.1	9	13.1
237B	75.5	7.4	0.6	7.4	9.1
237C	74.3	7.9	0.5	5.3	12
237D	76.6	6.9	0.4	7.2	8.9
285A	77.1	4.9	0.5	6.5	11

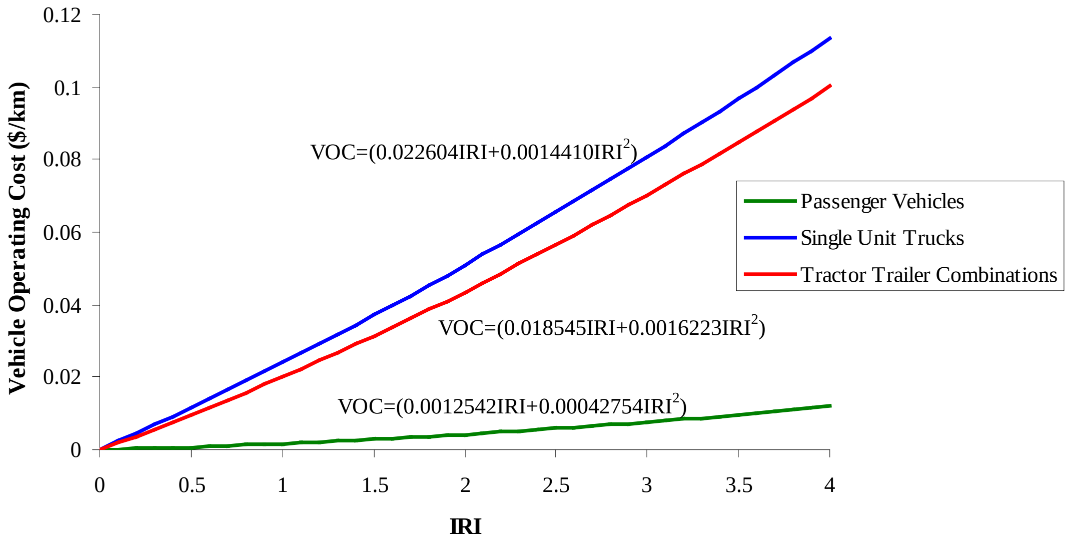


Figure F.1 Increased Vehicle Operating Costs as a Function of IRI

Appendix G – Draft Policy Objectives and Associated Strategies

The road authority in this Challenge has very recently generated a set of draft policy objectives and associated strategies, as listed in Table G.1. These are not intended to be "written in stone" but rather be the subject of discussion and improvement or modification with time.

Nevertheless, they provide a basis for establishing operational performance indicators or performance measures. The following two references may be directly useful (but it should be noted there are many other relevant references in the literature):

- Jurgens, Roy and Jack Chan, "Highway Performance Measures for Business Plans in Alberta", Proceedings, Annual Conference of Transportation Association of Canada, Calgary, September, 2005.
- Cowe Falls, Lynne and Ralph Haas, "Measuring and Reporting Highway Asset Value, Condition, and Performance", Report Prepared for Transportation Association of Canada, 2001 (Updated in Haas, Cowe Falls, and Tighe, "Performance Indicators for Properly Functioning Asset Management Systems", Proceedings, 21st ARRB and 11th REAAA Conference, Cairns, Australia, May, 2003)

Additionally, it should be emphasized that since investing in the message is a key part of the Challenge, the policy objectives, strategies, and performance indicators, as referred to herein, are certainly relevant to responding to the Challenge.

Table G.1 Draft Policy Objectives and Associated Strategies

Class	Strategies
Provide High Quality of Service to Users	• Maintain 90% of network at level of service (smoothness, functionality, and utilization) good or better (e.g. < 10% at fair or poor level)
Continually Improving Road Safety	• Reduction of accident rate by 1%/year or greater
Preservation of Investment	• Increase asset value by 1%/year or greater
Effective Communication with Stakeholders	• Maintain website which communicates up-to-date status of the assets to the public, managers, industry/institutions, etc.
Resource Conservation & Environmental Protection	• Recycle 100% of reclaimed materials and waste (asphalt, concrete, aggregates, etc.) • Monitor emissions (construction, materials production, etc.) at established standards
Institutional Productivity and Efficiency	• Provide human resource training, advancement opportunities, and work environment which keeps annual turn over at < 5% • Increase program cost effectiveness (ratio of level of service provided to road users weighted by km of road network and vehicle km of travel, divided by total road network expenditures) by 1% or greater annually
"Culture" of Technological Advancement	• Commit 2.5% of annual program budget to R & D (projects, academic institution grants, and contracts, in-house technical awareness focus, etc.

Appendix H – HDM-4 Calibration Factors

Table H.1 contains the HDM-4 resets/ calibration factors for the regional conditions.

Table H.1 HDM-4 Distress Calibration Values

Deterioration Model	Calibration Factor	Inter-urban	Rural
Wet/Dry Season SNP Ratio	K_f	1.0	1.0
Drainage Factor	K_{ddf}	1.0	1.0
All Structural Cracking – Initiation	K_{cia}	1.48	1.27
Wide Structural Cracking – Initiation	K_{ciw}	1.48	2.13
All Structural Cracking – Progression	K_{cpa}	0.16	0.19
Wide Structural Cracking – Progression	K_{cpw}	0.05	0.062
Rutting – Initial Densification	K_{rid}	0.5	0.5
Rutting – Structural Deterioration	K_{rpd}	1.3	2.5
Rutting – Progression	K_{rp}	0.24	0.52
Thermal Cracking – Initiation	K_{cit}	1.60	1.62
Thermal Cracking – Progression	K_{cpt}	0.14	0.10
Ravelling – Initiation	K_{vi}	2.0	2.0
Ravelling – Progression	K_{vp}	0.5	0.5
Pothole – Initiation	K_{pi}	2.0	2.0
Pothole – Progression	K_{pp}	0.25	0.25
Edge Break	K_{eb}	1.0	1.0
Roughness – Environmental Coefficient	K_{gm}	0.87	0.87
Roughness – SNPK	K_{snpk}	1.0	1.0
Roughness – Progression	K_{gp}	0.063	0.074
Texture Depth – Progression	K_{td}	1.0	1.0
Skid Resistance	K_{sfc}	1.0	1.0
Skid Resistance – Speed Effects	K_{sfcs}	1.0	1.0